The Rise of the Engineer: Inventing the Professional Inventor During the Industrial Revolution*

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Abstract
Why was the Industrial Revolution successful at generating sustained economic growth? One explanation that has been put forward is that there was a fundamental change in the way that new technology was developed during this period, yet current evidence for such a change remains largely anecdotal. This paper provides direct quantitative evidence showing that how innovation and design work was done changed fundamentally during the Industrial Revolution. This change was characterized by the professionalization of innovation and design work through the emergence of the engineering profession. I document the emergence of this new type of worker, show the contribution that engineers made to technology development during the Industrial Revolution, and provide a theoretical framework for understanding how this change in the innovation system could have acted as a mechanism allowing the economy to transition from a slow “pre-modern” growth regime into more rapid “modern” economic growth.

Keywords: Industrial Revolution, innovation, engineering, economic growth

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Technological progress played the central role in the Industrial Revolution. Much of the research on innovation during the Industrial Revolution has focused on the factors that led to the burst of inventive activity that took place in Britain in second half of the 18th century. Yet, as Joel Mokyr has pointed out, short bursts of technological progress have occurred many times in history. “The true miracle” he argues, “is not that the classical Industrial Revolution happened, but that it did not peter out like so many earlier waves of innovation” (Mokyr, 2004, p. 15).

Why was technological progress sustained? Some have argued that the explanation for this miracle of sustained technological progress is that the system through which new technology was developed changed in a fundamental way during the Industrial Revolution. Alfred North Whitehead, for example, believed that, “The great invention of the nineteenth century was the invention of the method of invention.”¹ Did such a change in the process of innovation take place during the Industrial Revolution? And if it did, what did the change look like?

This paper provides evidence showing that an important change took place in the way that innovation and design work was done in Britain, and that the timing of this change corresponds closely to the onset of the Industrial Revolution. The change I highlight was the professionalization of invention and design work through the emergence of the engineering profession. Engineering work, ranging from the invention of new mechanical devices to the design of new types of infrastructure, had been done before the emergence of professional engineers. However, historical evidence suggests that how engineering work was done changed in a fundamental way in the last quarter of the eighteenth century. Watson (1989), in his history of the Society of Civil Engineers, describes how (p. 1), “When John Smeaton described himself as a civil engineer for the first time...he identified a new profession” which combined “The craftsman’s fund of knowledge, based on natural genius and practical experience...with the assimilation of scientific principles.”

Such a change could have important implications for our understanding of this seminal event in economic history. However, current evidence on this change remains largely anecdotal. The primary contribution of this paper is to provide direct quantitative evidence documenting the changes in the innovation process that took place

¹Whitehead (1925), p. 96.
in Britain during the Industrial Revolution.

I begin by providing a simple theoretical model. The core of the model takes Adam Smith’s insight that specialization can increase productivity and applies it to productivity in the development of new inventions and designs, by a new group of specialists: professional engineers. This idea is then embedded into a standard endogenous growth model following Romer (1990). The model shows how a change in the way new innovations were developed may act as the mechanism through which an economy transitions from a slow “pre-modern” growth regime into rapid “modern” economic growth. This provides a framework for thinking about how the changes documented in my empirical analysis might have played an important role in the take-off into modern economic growth.

My empirical analysis begins with a brief examination of the characteristics that defined the new professional engineers that emerged during my study period. This is done using the biographies of over 400 engineers, over 300 manufacturers, and over 1500 others involved in science and technology from the *Oxford Dictionary of National Biography*. I apply natural language processing methods to these biographies in order to identify the activities (verb stems) specifically associated with engineers. This analysis shows that by far the activity most closely associated with engineers, relative to either successful manufacturers or non-engineers involved in science and technology, was “design,” as well as related activities such as “invent” and “patent.” In addition, engineers were involved in activities related to the construction or implementation of new designs, and ancillary activities such as consulting, reporting, and surveying. Notably, these defining characteristics changed very little across the study period and they are similar regardless of whether I identify engineers using the judgement of historians or individual’s self-reported occupations.

Next, I document the emergence of professional engineers and the impact of this group on the development of new inventions and designs in Britain during the Industrial Revolution. The engineering profession that emerged during this period was diverse, ranging from civil engineers such as John Smeaton and James Brindley to mechanical engineers such as Henry Maudslay and Joseph Bramah, with many engineers, such as James Watt and Marc Isambard Brunel, making contributions across multiple branches of engineering. To account for this, I use three different empirical
approaches to study different aspects of the emerging engineering profession.

My first approach is based on biographical information from the ODNB, which has the advantage of covering all types of engineering. The ODNB data reveal a dramatic increase in the share of engineers among the noteworthy Britons beginning in the third quarter of the eighteenth century. By the middle of the nineteenth century, engineers made up around 20% of all noteworthy individuals associated with science or technology, and over 2% of all of those who merited an ODNB biography.

My second approach draws on the British patent data. This analysis is of particular interest because it reflects exactly the type of reproducible inventions thought to have been central to driving economic growth. Confirming the patterns observed in the biographical data, the patent data show the growing importance of engineers to invention in Britain during the Industrial Revolution. Engineers were almost completely absent from the patent record prior to 1760, but they appeared in growing numbers after that point. By 1800-10, they accounted for around 10% of all patents, a share that rose steadily to 20% by the 1840s and then just under 30% by the 1860s. This rising importance of engineers, which closely corresponds to the timing of the acceleration of productivity growth in Britain, has not, to my knowledge, been systematically documented in existing work.²

The patent data also show that engineers were fundamentally different from other common types of inventors, particularly manufacturer-inventors, the other major group of patent holders. Most importantly, I document that engineers were more productive, generating more patents per decade than any other type of inventor, and patents of higher quality based on several available patent quality indicators. Engineers also operated differently than other types of inventors. For example, they were more likely to work with coinventors, a feature that may help explain their greater productivity. In addition, individual engineers patented across a substantially broader set of technology categories than any other type of inventor. Even within the career of individual inventors, I provide evidence that once someone began to describe their occupation as engineer they also began to operate differently, by working with more

²The closest a study has come to identifying this pattern that I am aware of is MacLeod & Nuvolari (2009) which focuses on the mechanical engineering (essentially machine and tool making) industry. Despite including the term engineering, this sector should not be confused with the engineers I study, who worked across a wide range of industrial sectors and technology types.
coinventors, and they became more productive. These patterns indicate that engineers represented a new type of inventor, rather than simply a relabeling of some existing type.

The third strand of my empirical analysis focuses on civil engineering. Using a combination of historical evidence and data covering major infrastructure projects undertaken in Britain after 1500, I provide evidence that the way civil engineering work was done changed in the second half of the eighteenth century. As Skempton (1996, p. vii) describes, “Works of engineering had been executed before 1760, some of considerable magnitude, but they could not provide sufficient employment to support a body of men trained in work of this kind...” However, “The state of civil engineering changed decisively in the 1760s... Engineers forming a small but distinguished group were now fully employed in consulting, designing, giving evidence to Parliament and directing works...” (Skempton et al., 2002, p. xxiv). Supporting this historical narrative, I provide evidence showing that prior to 1750, most major civil engineering projects were overseen by engineers without substantial prior training or experience. After 1750 major civil engineering projects were increasingly overseen by experienced engineers, such as John Smeaton, William Jessop, Thomas Telford, and John Rennie, that headed established firms and undertook numerous major projects. They also trained the next generation of engineers, most of whom had gained extensive experience working for established firms before being awarded major projects of their own. Thus, we can trace out the professionalization of civil engineering work occurring in parallel with the arrival of engineers as important producers of mechanical inventions documented in the patent data.

Together, these three mutually-reinforcing strands of analysis highlight the fundamental changes that took place in the way invention and design work was done during the Industrial Revolution. These changes were characterized by the emergence of a new profession, engineering, where design and invention were among the core occupational functions. These changes began in roughly the third quarter of the eighteenth century, just as the Industrial Revolution was taking off, and accelerated through at least the middle of the nineteenth century. The emergence of professional engineering was also reflected in other ways. The first professional societies for engineers emerged during this period, as did a specialized technical press. Notably, all of these develop-
ments occurred largely without substantial government intervention, a feature that set Britain apart from countries such as France.\(^3\)

The overall contribution of this paper is to show that how invention and design work was done changed in a fundamental way during the Industrial Revolution, and to provide a theory describing how this might have contributed to the transition to modern economic growth. The analysis is, therefore, a largely descriptive exercise, but one that has potentially important implications for our understanding a seminal event in economic history. Establishing the underlying cause for the changes that I document is beyond the scope of this paper, though probable causes include expanding markets and an increasingly rich and accessible knowledge base. One contribution of the model is to describe how such factors could have led to the emergence of a professional research sector, thereby setting in motion the changes documented in my empirical analysis.

1 Related literature

Naturally, this paper is closely related to the enormous literature focused on understanding the Industrial Revolution. Two strands within this broad literature are particularly related. One existing set of papers uses biographical sources to look at the careers of important inventors or innovators (Allen, 2009b; Meisenzahl & Mokyr, 2012; Howes, 2017; Khan, 2018). A second closely related set of work uses patent data to examine the British innovation system during the Industrial Revolution. Important contributions to this literature include Dutton (1984), MacLeod (1988), and Bottomley (2014), as well as a number of other papers discussed later.

Surprisingly, neither of these existing lines of work have documented, quantitatively, the emergence and growing contribution of the engineering profession during the Industrial Revolution.\(^4\) This difference is due in part to the substantially richer

\(^3\)See Supplementary Appendix 6 for further discussion.

\(^4\)The “quasi-professional” inventors discussed by Dutton (Ch. 6) are closely related to the engineers I focus on. However, without closely examining occupation data, Dutton did not make the connection to the emerging engineering profession. Perhaps the closest to my patent data analysis is MacLeod (1988), who did review inventor occupations. Surprisingly however, MacLeod failed to identify the rise of the engineering profession documented here, which leads her to conclude that the era of the professional inventor did not begin until well into the nineteenth century.
data used in this study, including combining information from patent and biographical sources, the use of additional information from the patent data not utilized by previous researchers, and the meticulous manual linking that allows me to identify individual inventors within the patent record. Some previous work has also tended to treat engineers as simply engine makers or makers of machine tools. Engineers made important contributions in these technological areas but, as I will show, engineers were uniquely diverse in the range of design and technological problems that they worked on. These differences may help explain why previous studies have not yet described the emergence and contribution of engineers documented here.

This study has implications for two lines of recent work related to the Industrial Revolution. One of these is a set of recent studies highlighting the importance of upper-tail knowledge during this period (Mokyr, 2005; Squicciarini & Voigtländer, 2015). My results provide clear support for the argument that upper-tail knowledge mattered for technological progress during this period. Another long-standing debate has to do with the importance of scientific knowledge in the Industrial Revolution. While I do not attempt to directly evaluate the importance of scientific knowledge in the work of engineers, historical evidence certainly supports the idea that engineers acted as a critical bridge, translating scientific knowledge into practical use. As Henry Robinson Palmer stated at the first meeting of what would become the Institution of Civil Engineers, in 1818, “An Engineer is a mediator between the Philosopher and the working Mechanic; and like an interpreter between two foreigners must understand the language of both.”

This paper is also related to existing work emphasizing the importance of en-

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5 For example, this study combines data on the occupations of patentees, patents technology classifications, and multiple measures of patent quality.

6 Mokyr (2005), for example, argues that “what mattered above all was the level of sophistication of a small and pivotal elite of engineers, mechanics and chemists.”

7 This debate stretches back to work by Landes (1969), Rosenberg (1974), and Mokyr (2002) and includes recent papers by Squicciarini & Voigtländer (2015), Khan (2018), Kelly & Ó Gráda (2020), and a recent book by Jacob (2014).

8 Quoted from ICE (1928), p. 2. Palmer continued that “The Philosopher searches into Nature and discovers her laws, and promulgates the principles on which she acts. The Engineer receives those principles and adapts them to our circumstances. The working Mechanic, governed by the superintendence of the Engineer, brings his ideas into reality.” Engineering was “a profession which required not only a knowledge of one leading branch of science, but many; not only of one leading art, but of an indefinite number...”
The closest paper in this vein is Maloney & Valencia Caicedo (2017), which highlights the contribution of engineers to growth during the Second Industrial Revolution, roughly one century after the main focus of my study. The key difference here is that I study the emergence of engineers and their contribution during the key decades of the Industrial Revolution.

Finally, my theoretical framework is related to existing theories describing the transition from pre-modern to modern economic growth, most notably Unified Growth Theory (Galor & Weil, 2000; Galor, 2011). What differentiates my theory from existing work is a focus on how a change in the innovation process, and specifically the emergence of a group specializing in invention and design work, could have provided a mechanism through which the transition to modern economic growth occurred. Naturally, I am not claiming that this was the only mechanism at work; there is plenty of evidence that other factors, such as the accumulation of human capital and a beneficial institutional environment, mattered. However, when coupled with my empirical results, my theory suggests that changes in the inventive process may have also been important.

2 Theoretical motivation

This section briefly describes a theory illustrating how the professionalization of invention could have contributed to the acceleration in the rate of growth that took place during the Industrial Revolution. Full details are provided in Appendix A.1.

The central feature of the model is the process through which new technologies are developed. This can be done either by non-specialists, who are mainly engaged in other productive activities, or by specialist researchers (engineers). A key assumption, supported by my analysis of the patent data, is that specialist researchers are more productive at generating new technologies than non-specialists. Thus, the core of the model reflects Adam Smith’s insight that specialization can increase productivity. Specialized research also involves some fixed cost, a standard assumption in models of innovation, while non-specialists may develop new ideas simply as a byproduct of their productive activities (e.g., learning by doing) without an up-front investment.

9Other related work includes Jones (2001), Hansen & Prescott (2002), and Peretto (2015).
The model incorporates two factors that seem likely to play a role in determining whether a professional research sector emerges. The first is the institutional environment, and specifically, whether existing institutions provide sufficient protection for inventors to profit from their new inventions. This feature connects the model to existing work, dating back to (North & Thomas, 1973), which argues that Britain’s unique institutional environment may have played an important role in allowing the Industrial Revolution to take off. The second factor is the ease with which potential professional researchers are able to access skills and useful knowledge. The rise of modern engineering would almost certainly not have been possible had access to certain practical skills and scientific knowledge not been readily accessible, or if Britain did not have a ready supply of the high-skilled craftsmen needed to implement new ideas. This feature connects the theory to existing work, such as Mokyr (2009) and Kelly & Ó Gráda (2020), which emphasize the importance of knowledge in the Industrial Revolution and argue that Britain was particularly well-endowed with such knowledge by the eighteenth century.\(^\text{10}\)

Starting from an initially low level of technology, the model exhibits three phases of development, though not all phases will necessarily occur. In the first, “pre-modern phase”, there is a low level of technology, all individuals specialize in production activities, and all new ideas are the result of serendipitous discoveries generated by workers mainly engaged in generating output. There is no professional research sector in the pre-modern phase because the limited knowledge base means that professional research is not sufficiently productive to make it worthwhile for any individual. Over time, serendipitous discoveries raise the overall level of technology in the economy (similar to the pre-modern period in Unified Growth Theory), but this process may be very slow.

As the technology level slowly rises, it may reach a point where enough knowledge is available to support the emergence of a dedicated research sector. This occurs because, in the standard Romer (1990) framework, the productivity of inventors is increasing in the knowledge base that they have to work with. However, the model

\(^{10}\)Existing work highlights a variety of factors that contributed to the availability of useful knowledge and craft skills in England during this period, ranging from the influence of Enlightenment culture to Britain’s well-developed apprenticeship system.
makes it clear that the transition to modern economic growth is not inevitable. In particular, for the transition to modern economic growth to begin, the cost of acquiring the necessary skills must not be prohibitive, and there must be institutions in place that allow professional researchers to profit from their discoveries.

If institutions provide inventors with sufficient protection, and they have access to knowledge at a sufficiently low time cost, then the slow accumulation of knowledge during the pre-modern period will eventually allow a dedicated research sector to emerge. If this occurs, then the emergence of a professional research sector causes an acceleration in the rate at which new technologies are developed. This acts as the mechanism through which the economy transitions toward a new balance growth path characterized by more rapid economic growth.\footnote{As the transition occurs, the share of the population employed as professional researchers initially grows and then stabilizes. Concurrently, the overall share of the population acquiring skills increases and then stabilizes. Serendipitous discoveries as a by-product of production continue to occur, but over time this source of new technology diminishes relative to the contribution of dedicated researchers.}

It is useful to note that the way that slowly rising technology during the pre-modern period eventually leads (under the right conditions) to a tipping point that launches the economy toward modern economic growth is a standard feature of models that aim to describe the transition from pre-modern to modern growth, such as Galor & Weil (2000) and Hansen & Prescott (2002). This feature also connects to the historical context I study. The discovery of key macroinventions such as Newcomen’s steam engine and Arkwright’s water frame provided incentives for follow-on research of the type that over time would come to be dominated by engineers. Viewed through the lens of the model, these inventions represent the final increment that pushed the economy over the tipping point into modern economic growth. We should not lose sight, however, of the fact that the model does not predict that such a transition was inevitable.

Finally, it is important to recognize that the core mechanism in the model, a change in the production process through which new technology is developed, differs from existing work emphasizing, on the one hand, changes in the availability of inputs into the technology production process (such as human capital) and, on the other, changes in the rewards for producing new technology (such as increasing market size.
or better institutional protections for inventors). While those factors are likely to be important, and are therefore incorporated into my theory, they are distinct from the mechanism I emphasize.

3 Defining an Engineer

What defined an engineer during the study period? Because the development of engineering education lagged the emergence of the engineering profession, engineers were not defined by a particular educational qualification, as they might be today. Nor were engineers defined by working in a specific type of industry or technology. As my later results show, engineers were in fact uniquely broad in the range of technologies they worked on. Instead, engineering is best thought of as an occupation defined by a particular set of functions or tasks.

Biographical information from the the *Oxford Dictionary of National Biography* can help us identify the tasks that characterized engineering. The ODNB is a rich data source that has been used in numerous previous studies, though it is important to keep in mind that it covers only the most successful or notable individuals.\textsuperscript{12} I begin by collecting the text of the biographies of all those classified by the ODNB as engineers who were born before 1850 (439 in total). I also collect data for two comparison groups: manufacturers (349 biographies) and those non-engineers classified as involved in science or technology (1547 biographies).\textsuperscript{13} Using natural language processing methods, I parse the biographies and identify all verb stems. These verb stems reflect the types of activities that individuals undertook during their lifetime. This procedure identifies 924 verb stems. I focus on the 338 verbs that appear in

\textsuperscript{12}Initiated in 1882 and regularly updated, the ODNB aimed to “supply full, accurate, and concise biographies of all noteworthy inhabitants of the British Islands and the Colonies (exclusive of living persons) from the earliest historical period to the present day” (Smith et al., 1917, p. lxii). The online version now includes over 60,000 biographical entries (see https://www.oxforddnb.com/). Previous studies using these data include Allen (2009a), Meisenzahl & Mokyr (2012), Nuvolari & Tartari (2011), and Khan (2018).

\textsuperscript{13}Within the ODNB, these are the two natural comparison groups. Most engineers were classified as part of those involved in science and technology, so it is natural to compare to that group. Manufacturers were the other major group of inventors during the study period, as the patent data will show. I exclude military engineers from the engineers group. I also include iron masters as manufacturers. Of those individuals classified as working in science or technology, I do not include manufacturers, artists/engravers, alchemists, or fossil collectors.
at least 100 out of the 2335 biographies used in the analysis. To provide a point of comparison, I identify a set of ‘neutral’ verbs (e.g., is, do, died, sat, etc.) that are unlikely to reflect activities associated with a particular occupation. I then run the following regression specification:

\[
VERB_{vi} = \sum_{v \in \tilde{V}} (\gamma_v \ ENG_i \theta_v) + \phi_i + \eta_v + \epsilon_{vi}
\]

where \(VERB_{vi}\) is an indicator for whether verb stem \(v\) shows up the biography of individual \(i\), \(\phi_i\) is a set of individual biography fixed effects, which accounts for variation in the length of individual biographies, and \(\eta_v\) is a set of verb fixed effects, to account for variation in the baseline frequency with which each verb is used. The explanatory variables of interest in this regression are constructed by interacting an indicator for whether an individual is an engineer (\(ENG_i\)), with \(\theta_v\), an indicator variable for each verb in the set of verbs \(\tilde{V}\) that excludes neutral verbs. The estimated coefficient for each verb in this set, \(\gamma_v\), reflects the extent to which that verb is particularly common in engineer biographies. Since I am looking at many outcomes, I adjust for multiple hypothesis testing by calculating sharpened p-values, following Benjamini et al. (2006) and Anderson (2008).

Table 1 presents the twenty verb stems most strongly associated with engineers.\(^{14}\) For all of these, the association is statistically significant at the 99% level after adjusting for multiple hypothesis testing (sharpened p-values below 0.01). The presence of verbs such as “design”, “invent” and “patent” indicate the important role of inventive activities to the engineering profession. Out of all the verbs, the one most closely associated with engineers is “design”. There are also terms indicating the role that engineers played in implementing their new designs and inventions, words such as “build,” “erect,” “employ,” “lay,” and “supervise.” Other important roles played by engineers are indicated by the presence of “consult,” “report,” and “survey.” These terms give us a sense of the types of activities that set engineers apart from others.

The words least associated with engineers can also be informative. When compared to manufacturers, the five verbs most associated with that group, relative to

\(^{14}\text{See Supplementary Appendix 2 for additional results and alternative specifications.}\)
analyses. This table presents the 20 words most strongly associated with engineers as well as estimated t-statistics from OLS regressions based on robust standard errors. Engineers are compared to manufacturers and non-engineers categorized as involved in science or technology in the ODNB. All of the coefficients associated with these verbs have sharpened p-values below 0.001. N=789,230 (2335 biographies x 338 verbs).

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<thead>
<tr>
<th>Verb</th>
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<tr>
<td>design</td>
<td>14.61</td>
<td>employ</td>
<td>6.74</td>
<td>complete</td>
<td>5.10</td>
<td>advise</td>
<td>4.40</td>
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<tr>
<td>build</td>
<td>11.53</td>
<td>report</td>
<td>6.23</td>
<td>open</td>
<td>5.01</td>
<td>supply</td>
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<tr>
<td>construct</td>
<td>9.58</td>
<td>erect</td>
<td>6.10</td>
<td>supervise</td>
<td>4.87</td>
<td>connect</td>
<td>4.24</td>
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<tr>
<td>consult</td>
<td>8.16</td>
<td>survey</td>
<td>5.59</td>
<td>improve</td>
<td>4.83</td>
<td>propose</td>
<td>4.11</td>
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<tr>
<td>patent</td>
<td>6.74</td>
<td>drive</td>
<td>5.27</td>
<td>lay</td>
<td>4.56</td>
<td>invent</td>
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</table>

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engineers, are “sell,” “expand,” “produce,” “manufacture,” and “buy.” For non-engineers involved in science and technology, the verbs most associated with that group, relative to engineers, are “publish,” “graduate,” “write,” “study,” and “collect.” The contrast between these terms and the words in Table 1 highlights the defining differences, in terms of activities, between these various groups.

It is also useful to look at whether the terms associated with engineers appear to have changed for later compared to earlier cohorts. To examine this, I estimate a separate interaction term between each verb x engineer variable and an indicator for whether an individual was born after 1800 (which divides the sample roughly in half). This analysis shows that only three verbs exhibit a statistically significant change in association with engineers over time. All three of these terms, “employ”, “erect”, and “improve”, are less associated with engineers in the post-1800 period than before. It is notable that all three of these terms seem more related to the implementation of new ideas and designs, rather than their development. If anything, this suggests that the design and invention functions may have been becoming even more central to the engineering profession over time, but any changes appear to have been small.

I can also study whether the activities associated with engineers are different when engineers are identified based on the self-reported occupation in the patent data rather than the classifications by historians from the ODNB used above. To compare these two definitions, I have manually matched patent holders to ODNB biographies for all
inventors who filed two or more patents during the study period. Of the roughly 2000 inventors who took out at least two patents, I am able to match 245 to ODNB biographies.

The first thing we can see with this matched data set is that the two ways of identifying engineers are quite similar. Of those with engineer as their modal occupation in the patent data who match to the ODNB, 84% are also classified as engineers in the ODNB data. Of those classified as engineers in the ODNB that also appear in the patent data, 71% appear as engineers in at least one patent. Thus, the occupations self-reported in the patent data appear to match fairly closely the categorizations applied by historians looking back over the career of an individual.

I use this matched data set to identify the verb stems most associated with engineers, as identified in the patent data, compared to other individuals who also had at least two patents but did not identify as engineers. When this is done, using the procedure described above, by far the strongest verb stem associated with engineers is “design,” exactly the one that is most strongly associated with engineers when they are identified based on the ODNB biography. For all verbs appearing in both data sets, the correlation between the estimated association with engineers in the patent data compared to the associations from the main ODNB data is 0.6. Thus, the core functions of engineers appear to be similar regardless of whether we are relying on the patent data or the ODNB to identify who qualifies as an engineer, or whether engineers are compared only to other patent holders, or to other individuals in the ODNB.

4 Rise of the Engineer: Evidence from Biographical Data

This section uses information from the ODNB to provide an initial view of the rising importance of engineers in Britain during the Industrial Revolution. This analysis provides a valuable complement to the more extensive analysis of patent data coming

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15 Since this requires a laborious manual matching procedure, it is infeasible to do this with every patent filer.
16 See Supplementary Appendix 4.13 for further details.
17 The share is 75% if we look at those who listed their occupation as engineer in at least one patent.
18 See Supplementary Appendix Table 3 for more complete results from the patent data.
next, because the ODNB covers successful individuals regardless of whether they obtained a patent. Figure 1 plots the share of engineers found in the ODNB relative to all ODNB biographies (left axis) or relative to all individuals classified as either in ‘science and technology’ or ‘manufacturing and trade’ (right axis). We can see that, up to the cohort born from 1725-49, engineers account for a very small share of ODNB biographies. However, starting with the cohort born in 1750-74, there is a dramatic rise in the share of engineer biographies, which accounted for over 2% of all biographies by the cohorts born in the first half of the nineteenth century. A similar increase in apparent when we compare engineers to all individuals classified as working either in science and technology (which includes most engineers) or relative to those working in manufacturing and trade (which also includes some engineers). By the first half of the nineteenth century, engineers accounted for over 20% of all notable individuals associated with science or technology.

Figure 1: Share of engineers in ODNB biographies, 1650-1849

![Figure 1: Share of engineers in ODNB biographies, 1650-1849](data:image/png;base64,iVBORw0KGgoAAAANSUhEUgAAAGQAAABdAQAAAABf3QxgAAAAAXN0b3J5 AHAAOGXr7mLAAAAAElFTkSuQmCC)

Data collected from the ODNB.

Note that the time-scale here is based on the year of birth, so it is not strictly comparable to some of the graphs I will present later, which are based on patent filing dates. However, as we will see, the rise of the engineer shown in Figure 1 will also be reflected in the patent data, despite the fact that these two analysis rely
on alternative ways of identifying who is an engineer. A similar rise is also found when studying Google Ngrams, which show a sharp rise in the use of “engineer” after 1740 (see Supplementary Appendix 1). These patterns are also consistent with existing historical evidence. As Christine MacLeod has carefully documented (MacLeod, 2007) engineers experienced a rising stature beginning in the 1760s and 1770s. This contrasts with the rather poor reputation of “the engineer” (often denoting a maker of engines, rather than engineer as we understand it today) in the first half of the 18th century. In 1744, for example, J.T. Desaguliers warned the readers of his Course in Experimental Philosophy about being “over run with Engineers and Projectors” who “draw in Numerous People into ruinous and unpracticable schemes.” This poor reputation had been overturned by the early 19th century, as symbolized by the erection of a colossal statue of James Watt in Westminster Abbey in 1834. What had changed? MacLeod (2007) argues (p. 59) that “the strongest case for revising the inventor’s reputation as an untrustworthy ‘projector’ stemmed from the country’s growing awareness of major technological achievements.”

5 Rise of the Engineer: Evidence from Patent Data

This section analyzes the emergence of engineers as a key group of inventors, drawing on information available from British patent data. I begin by describing the data before turning to the analysis.

5.1 Patent data

Patent data provide a unique window into the development of technology during the Industrial Revolution, including details on thousands of individual inventors and inventions. Of course, not all innovations were patented (Moser, 2012), and not all patents were for useful innovations (MacLeod et al., 2003). For this reason, it is important that the patent data analysis is complemented with results from the biographical data, discussed above, as well as evidence on civil engineering, in Section 6. However, many of the most important inventions of the Industrial Revolution, as well as thousands of other useful, if less famous, ideas, can be found in patent filings.

The patent data used in this study include the full listing of patents filed from 1700-1851, with details including inventor name, inventor occupation, patent title, and inventor address. The core of this data set was digitized from the two-volume Titles of Patents of Invention, Chronologically Arranged, produced by the British Patent Office (BPO) and published in 1854. I focus mainly on the information about inventor occupations, while also using the names to track the output of each inventor. Excluding patents communicated from abroad, this data set includes 12,622 patent-inventor observations covering 11,243 patents.

One reason to focus primarily on the 1700-1849 period is that patent laws were largely stable during that period. In 1852, there was an important patent reform act that lowered the cost of patenting substantially, leading the number of patents filed annually to increase from several hundred to several thousand (see Supplementary Appendix Figure 2). Thus, while I have digitized additional data for the 1850s and 1860s, and I will use them in some of the analysis, it makes sense to focus my main results on the 1700-1849 period.

The most important step in preparing the data for analysis was linking patents associated with the same individual. Because making these links as accurate as possible is important for this study, this was done using a careful manual linking procedure, described in detail in Supplementary Appendix 3.2. For each of the patent-inventor observations from 1700-1849, I match up patents filed by the same inventor using inventor name, year of patent, inventor address, patent subject matter (based on the patent title), and in some cases additional biographical information. Because I link manually using a fairly rich set of linking information, the chance that patents are incorrectly linked to a common inventor is low, though it is possible that I have failed to link some patents by the same inventor because insufficient information to form a conclusive link was available. However, there is no reason to expect that missing links are common or systematic across inventor types. This matching process

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20 Because I often estimate results by decade, I end my main dataset in 1849.
21 Woodcroft (1854b).
23 Patent data for years after 1851 were digitized from the Chronological Index of Patents prepared by the British Patent Office. A second reason to focus primarily on the 1700-1849 period is that, before the 1852 patent law change occupations were provided for most patent entries, but after 1852 the share of patents with missing inventor occupation data is substantial (around 20%).
identifies 8,328 unique inventors active during 1700-1849. Supplementary Appendix Table 6 lists the most prolific patent filers during that period.

The raw patent data include over 2,000 unique occupation strings. Several of these, such as “gentleman”, “esquire”, and “engineer” appear regularly. Many others, particularly those reflecting specific manufacturing trades (e.g., “Britannia-ware manufacturer”, “Candle-wick maker”) appear irregularly. To make this set of occupation strings manageable, I have cleaned them and grouped them into broad sets of related occupations. Table 2 provides counts of the occupation groupings used in the analysis for 1700-1849, while examples of specific occupations falling into each group are available in Supplementary Appendix 3.4.²⁴

Table 2: Broad occupation categories used in the main analysis, 1700-1849

<table>
<thead>
<tr>
<th>Industry</th>
<th>Patents</th>
<th>Industry</th>
<th>Patents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag/Food/Drinks</td>
<td>269</td>
<td>Merchants</td>
<td>635</td>
</tr>
<tr>
<td>Chemical Manuf.</td>
<td>474</td>
<td>Mining &amp; Metals</td>
<td>759</td>
</tr>
<tr>
<td>Construction</td>
<td>410</td>
<td>Misc. Manuf.</td>
<td>1562</td>
</tr>
<tr>
<td>Engineers</td>
<td>1,726</td>
<td>Textile Manuf.</td>
<td>957</td>
</tr>
<tr>
<td>Esquire</td>
<td>754</td>
<td>Prof. services</td>
<td>635</td>
</tr>
<tr>
<td>Gentry</td>
<td>1,745</td>
<td>Other</td>
<td>833</td>
</tr>
<tr>
<td>Machinery &amp; Tools</td>
<td>1,068</td>
<td>Unknown</td>
<td>795</td>
</tr>
</tbody>
</table>

Data cover 1700-1849. Excludes communicated patents.

Comparing the names and occupations listed in the patent data reveals that the occupations associated with specific inventors were sometimes not constant across

²⁴Given my focus on engineers, a couple of additional points about that occupation grouping are warranted. First, some inventors listing “engineer” as an occupation also list another occupation. This is not very common, but typically when it occurs the other occupation is some type of manufacturing. Individuals who list engineer together with a second occupation are counted as engineers in my analysis. Second, civil and other types of engineers (e.g. “consulting engineers”) are also counted as engineers for the purposes of my analysis. Third, I exclude from the engineers category those described as “engine makers” as well as mining engineers (which includes “coal viewers”). There is some question about whether these should be treated as engineers or instead classified with, respectively, the machinery manufacturers and miners so, in the Appendix, I also consider robustness results including these groups as engineers. Ultimately, this makes little difference because neither engine makers nor mining engineers are common. Military engineers are also excluded from the engineers category. They are treated the same as other military officers.
all of their patents. This typically reflected changes in occupation over the career trajectory of an inventor. An example is provided by the engineer Joseph Bramah, famous as a lock and tool maker. Bramah was trained as a carpenter and worked installing waterclosets before he turned his attention to developing new inventions. He first appears in the patent records, in 1778 (patent 1177) as a cabinet maker (consistent with constructing waterclosets). He appears as a cabinet maker again in 1783 and 1784 and then as an engine maker in 1785, 1790 and 1793. Only in 1795 does he begin appearing in the patent record as an engineer (a hydraulic press, his most important invention according to his ODNB biography). Thereafter his interests broaden and he appears in the patent record eleven more times, always as an engineer, with inventions ranging from a beer engine, a planing machine, a paper-making machine, a banknote numbering machine, and a fountain pen. This progression from manufacturer-inventor to engineer was a common pattern in the early days of engineering.

To deal with these changing occupations, when analyzing data at the patent level, I generally assign patents to the occupation group based on the occupation that appears in that patent’s entry. When an analysis is conducted at the level of individual inventors rather than patents (such as when looking at patents per inventor), it is necessary to identify a unique occupation for each inventor. In those cases, I typically use the modal occupation that appears across the patents that the inventor filed. In robustness exercises, I consider alternative approaches. In some of the analysis I also exploit changes in an inventor’s occupation over time to study whether inventors begin to behave differently once they start describing themselves as engineers.

I also use data that provide comprehensive categorizations of the technology type represented by each patent, constructed by the British Patent Office. The BPO index categorizes each patent into one, and occasionally more than one, out of 147 technology categories. To my knowledge this is the first use of the full digitized

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25 See his ODNB biography.
26 If an inventor does not have a unique modal occupation, then that inventor is excluded from the analysis. However, this results in the exclusion of just 362 out of the over eight thousand inventors in my analysis.
27 These categorizations were published as the Subject Matter Index of Patents of Invention in 1854 (Woodcroft, 1854a).
28 Supplementary Appendix 3.6 provides a listing of the top ten technology categories, by patents
BPO categorization data for the period before 1852. As a check on the results obtained using the BPO classifications, I also replicate my analysis using an alternative classification from Billington & Hanna (2018) generated by applying machine learning to the patent titles.

This study also uses several patent quality measures. During my study period, standard patent quality measures such as patent citations are not available. Instead, I use four alternative approaches to measuring patent quality. The first is based on the payment of patent renewal fees. The fees I study were introduced by the 1852 patent reform, so this measure is available only for patents in the 1850s and 1860s. The second set of quality measures that I use, based on references to patents in contemporary or modern publications, are from Nuvolari & Tartari (2011) and Nuvolari et al. (2019). This is the only quality indicator that is available across the full study period. The third quality measure is based on exhibits in the Great Exhibition of 1851, which has previously been used by Petra Moser to study innovation patterns (Moser, 2005, 2012). This measure is constructed by manually linking patent holders to Moser’s database of exhibits of patented inventions in the Great Exhibition. A fourth measure of patent quality is constructed by matching patent holders with at least two patents to the individual profiles of famous Britons in the ODNB.

5.2 Analysis of the patent data

Figure 2 describes the rising importance of engineers as inventors of patented technologies. Specifically, the figure shows, by decade, the share of patents with at least one inventor in a particular occupation group (top panel), and the number of patents with at least one inventor in each occupation group (bottom panel, log scale). The rise of the Engineer, starting in the 1760s and 1770s, is apparent. By 1800-10, 10% of patents had at least one engineer inventor. This rose to 20% by the 1840s. By

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29 These data come from Hanlon (2015). See that paper for further details on the source and construction of the renewals data.

30 See Supplementary Appendix 4.6 for further details on the exhibition data.

31 The shares in the top panel are relative to all patents for which an occupation is reported. This makes very little difference before the 1850s, but it matters for the last two decades because there was a large increase in patents that did not list an occupation after the 1852 patent reform.
the 1860s, engineers accounted for over 29% of patents for which an occupation was reported. No other group shows a similar pattern of growth across the study period. In the bottom panel we can see that patents by all types of inventors were growing during this period, but no other group experienced growth similar to the rate that we see for engineers after 1760. By the 1860s engineers produced far more patents than any other occupation group.

For a sense of the individuals that listed their occupation as “engineer”, Supplementary Appendix 3.5 provides a list of the top-five engineer patent filers in each decade. Prior to the 1760s, very few engineers appear in the patent data and even the top patenting engineers were generally obscure, with the exception of John Kay in the 1730s. However, this had changed by the 1780s, when we see the list topped by James Watt and William Playfair (inventor of the bar chart and pie graph, among other things), followed by Joseph Bramah and Richard Trevithick in the 1790s and the first decade of the 19th-century, Marc Isambard Brunel and Bryan Donkin in the 1810s, etc.

Three broad types inventors, described by MacLeod (1988, p. 78-9), can be discerned in Figure 2. First, there are the amateur inventors, for whom invention was “an amusing diversion that might one day open up a lucrative sideline.” Many of the gentlemen in Figure 2 probably fall into this group. The second group were the professional inventors, for whom “inventing was not a hobby but a livelihood. Typically he obtained a large number of patents across a wide field of industries...” We will see that engineers fit this description quite closely. The third group MacLeod called the businessman, “those who were ready to engage in manufacturing or trade...while they sometimes obtained more than one patent, these usually related only to their own branch of business.” This group, which I will call manufacturers, were the most common type of inventor outside of engineers. In the remainder of the analysis I will make a special point to study the differences between engineers and these manufacturer-inventors.

In Supplementary Appendix 4.1, I compare the pattern of patents by engineers to other groups thought have made an important contribution to innovation during the Industrial Revolution, such as watchmakers, millwrights, instrument makers, and machinists, or those that may have been related to engineers such as “engine mak-
Occupation groups are based on the occupations listed in the entry for each patent. Excludes communicated patents. Note that patents with multiple inventors may be counted in more than one category, so the shares may sum to more than one.
The main take-away from that analysis is that none of these groups are large compared to engineers, at least after 1760, and none of them experienced the type of explosive growth in patenting that engineers exhibited.

5.2.1 Differences in productivity, quality, and coinventors

In this subsection, I look at whether engineers were different from other types of inventors. Specifically, I study how many patented inventions individuals produced, the quality of their inventions, and whether they worked in teams with other inventors.

**Productivity:** Table 3 describes the average number of patents per inventor for inventors in each occupation group, where occupations are based on the modal occupation listed across each individual’s patents. We can see that Engineers generated far more patents per inventor than those in any other occupation group.

<table>
<thead>
<tr>
<th>Occupation group</th>
<th>Avg. patents per inventor</th>
<th>Occupation group</th>
<th>Avg. patents per inventor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag/Food/Drinks</td>
<td>1.258</td>
<td>Merchants</td>
<td>1.246</td>
</tr>
<tr>
<td>Chemical Manuf.</td>
<td>1.586</td>
<td>Mining &amp; Metals</td>
<td>1.436</td>
</tr>
<tr>
<td>Construction</td>
<td>1.188</td>
<td>Misc. Manuf.</td>
<td>1.372</td>
</tr>
<tr>
<td><strong>Engineers</strong></td>
<td><strong>2.069</strong></td>
<td>Textile Manuf.</td>
<td>1.463</td>
</tr>
<tr>
<td>Esquire</td>
<td>1.727</td>
<td>Prof. services</td>
<td>1.349</td>
</tr>
<tr>
<td>Gentry</td>
<td>1.571</td>
<td>Other</td>
<td>1.265</td>
</tr>
<tr>
<td>Machinery &amp; Tools</td>
<td>1.473</td>
<td>Unknown</td>
<td>1.152</td>
</tr>
</tbody>
</table>

Table 3: Average patents per inventor in each occupation group, 1700-1849

Inventor occupations groups are based on each inventor’s modal occupation. Those without a unique modal occupation group are excluded. Communicated patents are not included. Data cover 1700-1849, the years when matched data are available.

Table 4 verifies that the difference between engineers and other types of inventors is statistically significant and present in various sub-periods. The first column

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32 On watchmakers, see Kelly & Ó Gráda (2016). The role of millwrights is emphasized by Mokyr et al. (2020). Kelly & Ó Gráda (2020) highlight the role of instrument makers. Kelly et al. (2020) discuss the importance of artisanal mechanical skills such as those possessed by machinists and machine makers.
presents results looking across the full sample period. The estimates show that, indeed, engineers produced significantly more patents than other types of inventors. Moreover, magnitude of the coefficient on engineers, 0.689, is very large relative to the average number of patents per inventor, which is 1.52 across the full sample. For comparison, I also estimate results for manufacturer-inventors, a group that includes the Machinery & Tools, Metals & Mining, Chemicals, Textiles, and Misc. Manufacturing occupation groups. Unlike engineers, manufacturer-inventors are not more productive than other types of inventors.

We may worry that this difference is simply because engineers were operating in technology areas where patenting was more common. In Column 2, I include controls for the modal technology category that each inventor was working in. This has very little impact on my estimates, which indicates that differences in the propensity to patent across technology categories is not behind the higher productivity of engineers relative to other types of inventors. It is also useful to look at how these patterns look in various sub-periods of the sample. The results in Columns 3-6 show that I also obtain clear results within each twenty-year period from 1770-1849 (as shown above, there are few engineers before 1770 so I do not include results for that period). In contrast to engineers, those with manufacturing occupations did not generate more patents than the average inventor in any sub-period.

While the results in Table 4 identify engineers using the modal occupation appearing in an individual’s patents, and excluding those without a unique modal occupation, there are other reasonable alternative ways to classify engineers. I explore several of these in Supplementary Appendix 4.2 and find that all of the alternatives I consider show that engineers patented substantially more inventions than other types of inventors.

At this point it is worth considering whether the decision not to include engine builders or mining engineers as part of the engineers category has any bearing on the results I obtain. To examine this, in Supplementary Appendix 4.3, I present additional results following the approach used in Table 4 but classifying these groups as part of the engineers category. The results are effectively identical to those presented in Table 4, which signals that the decision of whether or not to classify engine builders

As Moser (2005) has shown, patenting rates can vary substantially across sectors.
Table 4: Number of patents per inventor regressions

<table>
<thead>
<tr>
<th></th>
<th>DV: Number of patents per inventor</th>
<th>All</th>
<th>All</th>
<th>1770-</th>
<th>1790-</th>
<th>1810-</th>
<th>1830-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>years</td>
<td>years</td>
<td>1789</td>
<td>1809</td>
<td>1829</td>
<td>1849</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
</tr>
<tr>
<td>Engineer</td>
<td>0.689***</td>
<td>0.616***</td>
<td>1.023**</td>
<td>0.802***</td>
<td>0.339***</td>
<td>0.448***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.0865)</td>
<td>(0.0903)</td>
<td>(0.468)</td>
<td>(0.237)</td>
<td>(0.131)</td>
<td>(0.0921)</td>
<td></td>
</tr>
<tr>
<td>Manufacturer</td>
<td>0.0618*</td>
<td>0.0272</td>
<td>0.0136</td>
<td>-0.0240</td>
<td>-0.0285</td>
<td>-0.00298</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.0325)</td>
<td>(0.0368)</td>
<td>(0.0579)</td>
<td>(0.0585)</td>
<td>(0.0580)</td>
<td>(0.0529)</td>
<td></td>
</tr>
<tr>
<td>Tech. cat. FEs</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Observations</td>
<td>7,966</td>
<td>7,966</td>
<td>652</td>
<td>1,209</td>
<td>1,802</td>
<td>4,215</td>
<td></td>
</tr>
<tr>
<td>R-squared</td>
<td>0.018</td>
<td>0.044</td>
<td>0.187</td>
<td>0.121</td>
<td>0.061</td>
<td>0.055</td>
<td></td>
</tr>
</tbody>
</table>

*** p<0.01, ** p<0.05, * p<0.1. OLS regressions with robust standard errors in parenthesis. The unit of observation is an inventor. Data cover 1700-1849. The outcome variable is the number of patents per inventor across all years (Column 1-2) or with 20-year periods (Columns 3-6). The explanatory variable is an indicator for whether the inventor’s modal occupation is engineer. Inventors without a unique modal occupation are not included. The regression in Column 2 controls for the modal technology category for each inventor looking across all of that inventor’s patents by including a full set of technology category fixed effects. In Columns 3-6, I control for the modal technology category for each inventor within each period. In all of these, if there is a tie for the modal category then one is selected randomly. Data cover 1700-1849, when matched data are available.

and mining engineers in the engineers category has no impact on my overall results. This should not be surprising given that these groups are small relative to the number of engineers in the data.

**Patent quality:** Next, I provide evidence showing that, in addition to producing more patents, engineers also produced higher quality patents and achieved greater overall career success. In Column 1-2 of Table 5, I measure patent quality using the payment of renewal fees to keep patents in force after, respectively, three or seven years. Renewals were expensive: £50 at three years and £100 at seven years, compared to the initial patent application fee of £25.\textsuperscript{34} As a result, only 18% of patents were renewed at year three and just 6.3% at year seven. The results in

\textsuperscript{34}For comparison, average annual nominal earnings for a worker in full time employment in 1851 were about £33. See \textit{measuringworth.com}.
Columns 1-2 show that patents with at least one engineer inventor were substantially more likely to be renewed. The effects are large in magnitude compared to the sample averages and strongly statistically significant. While patents by manufacturer-inventors were also more likely to be renewed, they were substantially less likely to be renewed than patents by engineers. Additional results using the patent renewal data are presented in Supplementary Appendix 4.4.

In Column 3 and 4 of Table 5, I consider a second measure of patent quality based on references in contemporary or modern sources. Column 3 uses the WRI (for Woodford Reference Index) compiled by Nuvolari & Tartari (2011), which is based only on contemporary sources. Column 4 uses the BCI (for Bibliographic Composite Index) from Nuvolari et al. (2019). The BCI augments the WRI with references in modern sources. In both cases the indexes have been standardized. The results suggest that patents with at least one engineer inventor were of higher quality than other patents. These patterns are particularly strong in the BCI index, which Nuvolari et al. (2019) argue is the more reliable measure. In contrast to the results in Columns 1-2, these measures suggest that manufacturer-inventors generated lower-quality patents than the average. More complete results obtained using the patent quality indices are available in Supplementary Appendix 4.5.

In Column 5, I use exhibiting in the Great Exhibition of 1851 as an indicator of quality. The sample is the set of all inventors who patented from 1830-1849 and the outcome variable is an indicator for whether a patent holder subsequently appeared as an exhibitor or inventor in the Great Exhibition. The regression estimates reflect how the probability of being in the Great Exhibition varies by occupation group. The results show that engineer patent holders were substantially more likely to exhibit patented inventions in the Great Exhibition than other patent holders. Further details and additional results using the Exhibition data can be found in Supplementary Appendix 4.6.

Finally, in Column 6, I look at an indicator of the overall career success of patent holders, as indicated by their inclusion among the noteworthy individuals in the ODNB. For each of the 2,053 inventors with two or more patents, I manually search for each individual in the ODNB. Engineers, identified based on the occupations listed in the patent data, made up 15.5% of the group that I attempted to match to the
ODNB database, but they account for 26.9% of those found in ODNB, and 34.2% of those matched who were born after 1780, an indication that engineers were more likely to achieve substantial career success than other types of inventors.

Table 5: Patent quality regressions

<table>
<thead>
<tr>
<th>Year Three WRI</th>
<th>Year Seven BCI</th>
<th>Great Exhibition</th>
<th>ODNB Biography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineer</td>
<td>0.0462***</td>
<td>0.0200***</td>
<td>0.0441***</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>0.0140*</td>
<td>0.00870*</td>
<td>-0.0486*</td>
</tr>
</tbody>
</table>

*See table notes for details on fixed effects included in different specifications.

Column 6 of Table 5 provides further evidence on this pattern. The regression
presented in that column is run over all inventors searched for in the ODNB database (those with two or more patents) and the outcome is an indicator for whether an individual is found in the ODNB. The explanatory variable is the modal occupation of each inventor. These results indicate that engineer inventors were about 8 percentage points more likely to appear in the ODNB than other inventors with at least two patents, while manufacturer-inventors were less likely to be noteworthy enough for inclusion. These are large differences given the sample average rate of inclusion is 12.8%. Further ODNB results are available in Supplementary Appendix 4.7.

Overall, the results in Table 5, together with the more complete regression results available in the associated appendices, shows that, across a range of different quality indicators, engineers generated higher quality patents and had greater overall career success than other types of inventors. This is true relative to all inventors or to manufacturing-inventors in particular. Next, I consider other ways in which engineers differed from other inventors.

**Coinventor teams** One reason that engineers may have been more productive is that, because invention and design was central to their profession, they may have been better able to form coinventor teams. Coinventor teams may have been beneficial either because they brought together individuals with complementary technical skills, or because they helped inventors partner with those who were more able to fund or commercialize inventions. Across the study period, coinvention was generally rising, a pattern that has also been documented in more recent periods (Jones, 2009).

Table 6 presents regression results where the unit of observation is the patent, the outcome variable is whether the patent has more than one inventor (10.7% of all patents), and the key dependent variable is whether one of the inventors is an engineer. Column 1 presents baseline results using OLS regressions while Columns 2 and 3 add in decade and technology category fixed effects respectively. Columns 4-6 follow the

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35 This sample mean differs from the 11.9% of inventors with 2+ patents found in the ODNB because it includes only inventors with a unique modal occupation.

36 It is not possible to clearly differentiate these alternative motivations. However, in Supplementary Appendix 4.8 I explore the composition of these coinventor teams. This analysis indicates that engineers often co-invented with manufacturers or gentlemen, which may reflect the formation of partnerships between inventors and those who were well-placed to commercialize a new invention, or those who could contribute financing or political connections to a project, though it could also reflect different types of skills useful in the invention process.
same format, but using Probit regressions. These results show that patents by engineers involved significantly more co-inventors than patents filed by other types of inventors. The results are strongly statistically significant as well as large relative to the average rate of multi-inventor patents of 0.107 across the full sample. Thus, these findings indicate that engineers went about the process of invention in a way that differed markedly from other inventors.

Table 6: Patenting with co-inventors

<table>
<thead>
<tr>
<th>DV: Indicator variable for patents with multiple inventors</th>
<th>OLS regressions</th>
<th>Probit (marginal effects)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>Engineer</td>
<td>0.0663***</td>
<td>0.0582***</td>
</tr>
<tr>
<td></td>
<td>(0.00974)</td>
<td>(0.00984)</td>
</tr>
<tr>
<td>Decade FEs</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Tech. Cat. FEs</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Observations</td>
<td>11,243</td>
<td>11,243</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.006</td>
<td>0.013</td>
</tr>
</tbody>
</table>

*** p<0.01, ** p<0.05, * p<0.1. Data cover 1700-1849. In Columns 1-2 and 4-5 the unit of observation is a patent and robust standard errors are used. In Columns 3 and 6 the unit of observation is a patent-by-technology-category, so patents listed in multiple technology categories may appear more than once. To account for that, standard errors are clustered by patent. The explanatory variable is an indicator for whether one or more of the inventors is listed as an engineer in the patent entry.

Summary: The results in this subsection show that engineers generated more patents than other inventors, that on average these patents were of higher quality than those produced by other inventors, and that they worked with more co-inventors. One may wonder at this point whether these differences were due mainly to the selection of more productive individuals into engineering. To address this issue, in the next section I consider how the behavior of individuals change when they begin to think of themselves as engineers rather than manufacturer-inventors.

Note that in Columns 3 and 6 the number of observations increases because patents listed in more than one technology appear more than once, and to account for this standard errors are clustered by patent.
5.2.2 Changes upon becoming an Engineer

As the description of Joseph Bramah’s career in Section 5.1 illustrates, when engineering was still a relatively new profession a number of engineers first appear in the patent data as manufacturer-inventors or other types, and then eventually began to think of themselves instead as engineers. Using these occupation switchers, I can study whether the behavior and output of an inventor changes when they begin to describe themselves as an engineer.

To undertake this analysis, I begin by focusing on only those inventors with two or more patents (around 1900 inventors). For each inventor, I construct a dataset that covers all years from their first to their last patent and indicates the number of patents they filed in each intervening year. There are 380 inventors with multiple patents that list themselves as engineers in at least one patent. For these, I identify the first year that they list their occupation as engineer and generate an indicator variable that takes the value of one for that year and all subsequent years until the last patent that they filed. I then run regressions looking at how outcomes for each of these inventors changes after they began describing themselves as an engineer, with individual fixed effects included so that identification is driven entirely by changes within inventors over time. Specifically, I study how becoming an engineer is related to whether an inventor works with coinventors (their behavior) and how many patents they produce per year (their productivity).\(^{38}\)

The results are presented in Table 7. The first three columns of this table focus on one observable measure of the behavior of inventors: the share of their patents filed with at least one coinventor. The results in the first column show that individuals began working with more other inventors once they became engineers. To ensure that this wasn’t just due to becoming more experienced as inventors, the second column includes a control for the number of years since each inventor’s first patent. In the third column, I drop observations from the first year in which an inventor listed their occupation as engineer. This changes the sample, since it eliminates those who did not have patents in years after they first list their occupation as an engineer (about 18%\(^{38}\))

\(^{38}\)Unfortunately, it is not possible to also assess how patent quality changes when inventors become engineers, since the only quality measures available across the full study period, the reference-based indexes, are too noisy to generate clear results given the sample size used in this analysis.
of engineers), but we still see evidence that inventors worked with more coinventors after becoming engineers.

In Column 4-6, I look at the output of inventors, specifically the number of inventions they produced per year, between the first and last year that they patented. The results in the first column show that individuals generated about 0.25 more patents per year after they started describing themselves as engineers. This is a large increase relative to the sample average of 0.32 patents per year. Column 5 shows that this is not due to a general increase in patenting as inventors’ careers progressed. In Column 6, I drop from the sample the first year in which an individual described themselves as an engineer. This is done because to become an engineer the individual must appear in the patent database, which causes a direct link between becoming an engineer and generating a patent. Dropping this ensures that this mechanical effect is not behind my results. I still observe clear effects in Column 6 despite the fact that these results are likely to be biased toward zero (the true magnitude of the change should lie between the estimates in Columns 5 and 6). Additional results, in Supplementary Appendix 4.9, show that even stronger effects are estimated if quadratic controls for time since first patent are included.

The fact that the same individuals begin to behave differently, and produce more, once they begin describing themselves as an engineer, indicates that the broad differences between engineers and other inventors documented above are not merely due to the selection of more productivity individuals into the engineering profession. Instead, these results suggest that once an individual began to think of themselves as an engineer, their behavior changed in a way that led to increased inventive output.

### 5.2.3 Differences in technology type and scope

In the next stage of the analysis, I bring in the British Patent Office technology categorizations and use them to study differences between engineers and other inventors in terms of the types of technologies that they worked on. A starting point for this analysis is Table 8, which describes the technology categories where the largest share of patenting inventors were engineers. We can see that engineers made up a

---

39Note that the sample size is larger in Columns 4-6 than in Column 1-3 because the sample in Column 4-6 includes inventors who never had a multi-inventor patent.
Table 7: Within-inventor regressions

<table>
<thead>
<tr>
<th></th>
<th>DV: Share of patents with multiple inventors</th>
<th>DV: Patents per year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1) (2) (3) (4) (5) (6)</td>
<td>(1) (2) (3) (4) (5) (6)</td>
</tr>
<tr>
<td>Engineer</td>
<td>0.0513*** 0.0620*** 0.0915*** 0.252*** 0.266*** 0.0686**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.0229) (0.0235) (0.0305) (0.0334) (0.0335) (0.0328)</td>
<td>(0.0229) (0.0235) (0.0305) (0.0334) (0.0335) (0.0328)</td>
</tr>
<tr>
<td>Years since</td>
<td>-0.000928 -0.000755 -0.00123*** -0.000624</td>
<td></td>
</tr>
<tr>
<td>first patent</td>
<td>(0.000605) (0.000575)</td>
<td>(0.000605) (0.000575)</td>
</tr>
<tr>
<td>Individual FE</td>
<td>Yes Yes Yes Yes Yes Yes</td>
<td></td>
</tr>
<tr>
<td>Dropping first year as Eng.</td>
<td>Yes Yes Yes Yes Yes Yes</td>
<td></td>
</tr>
<tr>
<td>Observations</td>
<td>5,333 5,333 5,152 18,787 18,787 18,641</td>
<td></td>
</tr>
<tr>
<td>R-squared</td>
<td>0.547 0.548 0.552 0.234 0.234 0.233</td>
<td></td>
</tr>
</tbody>
</table>

*** p<0.01, ** p<0.05, * p<0.1. Standard errors are clustered by individual. The Engineer variable is an indicator for each individual that takes a value of one starting from the first year in which an individual listed their occupation as engineer in a patent, and zero otherwise.

substantial fraction of inventors in a number of key Industrial Revolution technology categories, such as machine tools (boring, drilling, punching), steam engines, and railways. Further evidence, in Supplementary Appendix 4.10, shows that while engineers were important in these categories, as a group they also patented across a wide range of different technology types.

Table 9 presents the average number of technology categories patented in by inventors falling into each occupation group. Clearly engineers worked across a broader set of technology categories than any other type of inventor. This was not due to the fact that many patents by engineers were filed later in our study period. Regression results in Supplementary Appendix Table 4.11 show that not only did engineers work on significantly more technology types when looking across the full sample period, but the same is true in every two-decade sub-period from 1770 forward (we know from above that there were few engineers before 1770). In contrast, inventors holding manufacturing occupations consistently patented in fewer technology categories, most likely those closely related to their manufacturing activities.
Table 8: Technology categories with a high share of patents from Engineers

<table>
<thead>
<tr>
<th>Technology category</th>
<th>Share by Engineers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boring, Drilling, Punching</td>
<td>0.622</td>
</tr>
<tr>
<td>Steam; Steam-Engines and Boilers.</td>
<td>0.517</td>
</tr>
<tr>
<td>Boilers and Pans</td>
<td>0.484</td>
</tr>
<tr>
<td>Railways and Railway Rolling-Stock</td>
<td>0.419</td>
</tr>
<tr>
<td>Gas Manufacture and Consumption</td>
<td>0.400</td>
</tr>
<tr>
<td>Bridges, Arches, Viaducts, Aqueducts</td>
<td>0.356</td>
</tr>
<tr>
<td>Air and Wind: Air and Gas Engines and Windmills</td>
<td>0.351</td>
</tr>
<tr>
<td>Turning</td>
<td>0.333</td>
</tr>
<tr>
<td>Tunnels, Excavations, And Embankments</td>
<td>0.286</td>
</tr>
<tr>
<td>Smoke Prevention. -Consumption Of Fuel</td>
<td>0.284</td>
</tr>
<tr>
<td>Measuring And Numbering</td>
<td>0.283</td>
</tr>
<tr>
<td>Motive Power and Propulsion</td>
<td>0.282</td>
</tr>
<tr>
<td>Casks And Barrels</td>
<td>0.280</td>
</tr>
</tbody>
</table>

This table lists the share of patents within a technology category with “engineer” listed as the occupation, excluding communicated patents. Data cover 1700-1849.

Thus, engineers were not merely generating more inventions of the same type. Instead, they were producing both more inventions and inventions that spanned a wider set of different technologies. In this, they appear to have been fundamentally different than other types of inventors. It is worth noting that engineers typically did not produce patents in more technology types per patent filed. Rather, their diversity on technology categories covered was closely tied to the fact that they were producing more patents overall. However, this does not detract from the fact that they were able to patent in a broader set of technologies, because it may be that their greater overall productivity was possible exactly because they possessed the ability to pursue promising ideas across a broader range of technology types.

One might wonder about the extent to which the technology category results are

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40It is important to note that these results do not contradict the idea, emphasized in recent work by Jones (2009), that inventors become more specialized as knowledge advances. Rather, the growth of specialized inventors (engineers) should be interpreted as the first step in this specialization process. Moreover, the fact that engineers were more likely to work in co-inventor teams is also consistent with what we would expect given the results in Jones (2009).
dependent on the specific features of the BPO classifications. To allay this concern, Supplementary Appendix 4.12 shows that equivalent results are obtained using a very different set of patent classifications generated by Billington & Hanna (2018).

Table 9: Average number of technology categories per inventor, by occupation type

<table>
<thead>
<tr>
<th>Occupation group</th>
<th>Avg. number of tech. categories per inventor</th>
<th>Occupation group</th>
<th>Avg. number of tech. categories per inventor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agric., food/drink makers</td>
<td>1.548</td>
<td>Merchant</td>
<td>1.483</td>
</tr>
<tr>
<td>Chemical manuf.</td>
<td>1.740</td>
<td>Metals and mining</td>
<td>1.589</td>
</tr>
<tr>
<td>Construction</td>
<td>1.470</td>
<td>Misc. manuf.</td>
<td>1.462</td>
</tr>
<tr>
<td><strong>Engineering</strong></td>
<td><strong>2.459</strong></td>
<td>Textile Manuf.</td>
<td>1.388</td>
</tr>
<tr>
<td>Esquire</td>
<td>1.897</td>
<td>Prof. services</td>
<td>1.605</td>
</tr>
<tr>
<td>Gentry</td>
<td>1.822</td>
<td>Other occ.</td>
<td>1.490</td>
</tr>
<tr>
<td>Machinery and tool manuf.</td>
<td>1.547</td>
<td>Unknown</td>
<td>1.519</td>
</tr>
</tbody>
</table>

Based on the modal occupation group of each inventor. Inventors without a unique modal occupation group are not included. Excludes patents that are communications. Data cover 1700-1849.

5.2.4 Background of engineers

Using the matched patent-ODNB data (discussed in more detail in Supplementary Appendix 4.13), it is possible to study the background of engineers and compare these to other types of patent holders. The most common educational background for engineers was an apprenticeship. Prominent engineers apprenticed in a wide variety of older occupations, such as millwrights, watchmakers, carpenters, merchants, land surveyors and civil engineers, shipbuilders, coal viewers, etc. Of these, the most common for engineers was carpenter or joiner. In later years, some engineers also apprenticed at famous engineering firms, such as Boulton & Watt’s Soho Foundry in Birmingham or Galloway & Sons in London. The wide range of different apprenticeship backgrounds emphasizes the broad set of paths that led into engineering as well as the fact that engineering was not merely a relabeling of an older occupation such as millwright. Engineers were also more likely than other types of inventors to have
a purely working background (beyond basic primary schooling). A number of prominent engineers fell into this group, including the railway engineer George Stephenson and Richard Trevithick, the inventor of the high-pressure steam engine. Engineers were less likely than other inventors, particularly gentlemen and other professionals, to have formal higher education. This suggests that what higher education they did have was probably primarily due to self-study, a feature that appears regularly throughout the ODNB biographies. One implication of this fact is that it would be a mistake to classify this important group of inventors based on their formal educational background.

5.2.5 Summary

This section describes the emergence of engineers as an important group of patenting inventors. The timing of this emergence corresponds fairly closely with the onset of the Industrial Revolution, consistent with the patterns observed using biographical data. Importantly, engineers in the patent data appear to be fundamentally different than other types of inventors, in terms of how productive they were, how often they worked as part of inventor teams, and in the types of technologies they developed. This is true even when accounting for selection by looking at occupation changes across individual’s careers. These features suggest that the emergence of engineering reflects a fundamental shift in the British innovation system.

Of course, many of the designs created by engineers, particularly civil engineers were never patented (though a number civil engineers, including John Smeaton, did take out patents). In the next section, I provide complementary evidence documenting the changes that were taking place in civil engineering.

6 The Professionalization of Civil Engineering

Civil engineering work is perhaps the most closely associated with the engineering profession, and it was the first to develop many of the features of a profession, such as dedicated professional societies. Perhaps because of this, the development of civil engineering has received substantial attention from historians. This section reviews available historical evidence on the development of the civil engineering profession,
supported with some new quantitative analysis. Because of the nature of the data, the empirical analysis in this section is limited, but the discussion provides an important complement to the analysis of patent data.

While civil engineering work has been undertaken for millennia, historians highlight the fundamental changes that took place in how this work was done during the eighteenth century. Bill Addis, in his monumental history of 3000 years of building engineering (Addis, 2007), titles the chapter covering 1750-1800, “Engineering becomes a Profession.” In it, he describes how this professionalization was reflected in the career of John Smeaton, one of the leading civil engineers of the age (p. 239-240):

[John] Smeaton was able to apply general principles, based on science and tested using full-sized and scale model experiments, to an engineering problem in a field entirely unfamiliar to him...the translation of real engineering problems into simplified theoretical models was becoming a matter of course for the few engineers who were scientifically and mathematically educated...from Smeaton’s calculations of the size or number of water wheels needed to perform pumping duties, we can see that he had already established our modern approach to engineering design...While Smeaton has become an engineering icon...many other engineers where treading similar paths.

Similarly, the famous engineer William Fairbairn (1859), wrote in 1859 that, “At the commencement of 1750 the title of Engineer was unknown to the vocabulary of science. It was reserved for Brindley and Smeaton to establish a distinct profession under that name.”

It is possible to provide some quantitative support for this narrative using a list of 338 major British civil engineering projects. These data, from Skempton et al. (2002), have been digitized and combined with biographical information on the engineers involved. While the data cover 1500-1830, I focus mainly on the period after 1600, since there were few major projects before that point.

Figure 3 describes the share of major British civil engineering projects that were the first major project undertaken by the chief engineer (open diamond symbols).

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41Further details on these data can be found in Supplementary Appendix 5.
From 1600-1760, roughly 75% of major engineering projects were overseen by someone who had not previously overseen another major project. The only major exception to this is in 1640-1659, when the Dutchman, Cornelius Vermeyden, oversaw several important drainage works. It is notable that this pattern persists into the 18th century despite the substantial increase in the number of projects available after 1690 (see Supplementary Appendix Figure 6). After 1760, however, the pattern changes. From that point until 1830, roughly 35% of all major projects were overseen by a chief engineer who had not already overseen a major project. The second series in Figure 3 (filled circles) shows the number of first time project by individuals who had not previously trained under a more experienced engineer. After 1760, we can see that very few projects were overseen by engineers who did not either have prior experience or training under a more experienced engineer. Thus, the engineers chosen to oversee major projects were becoming a more experienced group.

What changed in the middle of the eighteenth century? Before 1760, major infrastructure projects were often designed and overseen by skilled craftsmen as one-off endeavors. Certainly there were some exceptions, such as Vermuyden and George Sorocold, who engineered several important water supply schemes in the 1690s and the first decade of the 18th century. Many of these “proto-engineers,” with backgrounds that included millwright, architect, surveyor, mason, and mining engineer, were skilled, and some were brilliant. What was different was that they had rarely developed their skills by working on previous major engineering works, and they rarely undertook more than one or two important engineering projects in their lifetime.

One striking example of this pattern is provided by the construction of the Westminster Bridge, the most expensive infrastructure project undertaken in Britain the first half of the eighteenth century. Parliament chose Charles Labelye as the engineer in charge of this project. There is plenty of evidence that Labelye was skilled and knowledgeable, but up to that time he had not a single major engineering project to his name, either as chief engineer or as an assistant engineer under someone more experienced (Skempton et al., 2002). That Parliament chose him to undertake the most

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42 This data set is generated through a laborious manual review of the biographies of every engineer that oversaw a major project in the data. I begin the graph in 1680 because before that point I am not confident that the available biographical information is detailed enough to identify the training for most engineers.
important engineering project of the period was emblematic of how civil engineering was done up to that point.

After about 1760, this pattern begins to change, with the emergence of a more professional body of engineers, each overseeing numerous major engineering works. From 1700-1750, for example, the most prolific individuals on Skempton’s list, Thomas Steer and John Reynolds, oversaw four major projects each. From 1750-1800, the most prolific engineer, John Smeaton, oversaw eighteen, followed by William Jessop (15 projects), John Rennie (9 projects), James Brindley (8 projects), etc. By 1800, the idea that a project such as the Westminster Bridge would have been awarded to an engineer with no prior experience would have seemed absurd.

43 Between 1750 and 1770, for example, Smeaton was responsible for the Eddystone Lighthouse, the Colstreet Bridge, work on the Perth Bridge, the Potteric Carr Drainage, work on the London Bridge Waterworks, and the Adlingfleet Drainage. In just the first decade of the 19th century, John Rennie built the Kelso Bridge, the Leith East Docks, the London Docks, the East India Docks in London, the Humber Dock in Hull, and oversaw the drainage of the Wildmore Fens. Further evidence on this patterns is provided in Supplementary Appendix Table 28.
One aspect of the professionalization of the civil engineering that took place after 1760 was that young engineers typically gained extensive experience as assistant engineers before overseeing major projects. From 1700-1760, my data show that only 20 percent of engineers undertaking their first project had prior experience working under an engineer who had previous experience on a major project. Neither John Smeaton, who undertook his first major project in 1756, nor James Brindley, who undertook his first major project in 1759, had previously worked for another engineer on a major project.

This changed in the generation that followed Smeaton and Brindley. After 1760, more than half of all engineers overseeing major projects were trained by more experienced engineers. Smeaton trained five engineers who would go on to oversee major projects, including William Jessop, who oversaw his first major project in 1779. Brindley trained six, including Robert Whitworth, who undertook his first major project in 1774. Jessop would go on to train or partner with seven later engineers who oversaw major projects; Whitworth would train six. John Rennie, perhaps the most prolific civil engineer of the late eighteenth century, had gained experience working for James Watt, who worked as a civil engineer while developing his famous steam engine innovations. Rennie would go on to train twelve engineers who would oversee major projects by 1830. Thus, we can see the profession of civil engineering develop after 1760, as the knowledge and experience of the first generation of professional civil engineers, such as Smeaton and Brindley, was passed on to the next.

The growth of engineering into a distinct and respected profession was accompanied by the development of institutions that helped engineers meet one another and exchange ideas. The Society of Civil Engineers was founded in 1771, followed by the Institution of Civil Engineers 1818 and the Institution of Mechanical Engineers in 1846. These provided a forum for engineers to engage, a way to present and publish their new ideas, and a representative of their interests. There was also a growing specialized press focused on disseminating engineering knowledge, including William Nicholson’s *Journal of Natural Philosophy*, founded in 1797, Alexander Tilloch’s *Philosophical Magazine* (1798), and, later, *Mechanic’s Magazine*, founded in 1823 by Joseph Clinton Robertson, an engineer. Thus, by the middle of the nineteenth century British engineers were immersed in a rich intellectual milieu based on
networks formed through the learned societies and information transmitted through a vibrant scientific and technical press, while the profession itself rested on institutional foundations that would survive to today.

Civil engineering maintained close ties with other branches of the engineering profession during the study period, including the mechanical engineers found in the patent data. These various branches of the profession shared professional societies, where they regularly interacted, and relied upon the same specialized publications. Many engineers were involved in both civil and mechanical engineer projects. This was true for James Watt, who worked as a civil engineer and surveyor while at the same time developing and commercializing his separate condenser.44 Marc Isambard Brunel, perhaps best known for mechanizing the manufacture of blocks for the Royal Navy (and as the father of the famous civil engineer Isambard Kingdom Brunel), worked as a civil engineer while developing numerous inventions (eighteen patented). Another example is provided by George Stephenson, who’s civil engineering work laying out railways such as the Stockton and Darlington was intimately linked to his mechanical engineering work on railway locomotives.

So, the rise of engineers as an important group of inventors shown in the patent data paralleled by the professionalization of civil engineers as designers of a wide variety of civil infrastructure. These various strands of engineering were closely tied to one another, with many engineers moving between them, and in a number of cases we see civil engineers filing patents, or mechanical engineers relying on income from civil and consulting work while at the same time developing new inventions on the side.

7 Conclusions

In The Wealth of Nations (1776), Adam Smith wrote that “All the improvements in machinery, however, have by no means been the inventions of those who had occasion to use the machines...”45 Many improvements were made by what he called “philosophers, or men of speculation...whose trade it is not to do anything but to

44He would become a member of the Society of Civil Engineers in 1789 (Watson, 1989), following his partner, Matthew Boulton, who was elected to the society in 1780.
45Smith (1902), book 1, p. 51.
observe everything; and who, upon that account, are often capable of combining together the most distant and dissimilar objects.” Smith predicted that “In the progress of society, philosophy or speculation becomes, like every other employment, the principal or sole trade and occupation of a particular class of citizens.” While Smith was writing at the very dawn of the emergence of engineers, he was already able to appreciate the potential benefits of a division of labor that allowed one group of workers to specialized in invention and design.

This paper documents the emergence of this new division of labor, characterized by the emergence of professional engineers, and by doing so it provides a new perspective on the Industrial Revolution. Central to this perspective is the idea that there was a change in the process through which new technology developed, an innovation in the process of innovation. I am certainly not the first to argue that the innovation process changed in important ways during this period. What is new here is backing that argument up with quantitative evidence, describing in more detail the nature of the change, and showing, theoretically, exactly how such a change might have contributed to the transition to modern economic growth.

It is not my intention to argue that the changes documented here mattered to the exclusion of other factors that may have influenced the innovation rate during the Industrial Revolution, such as an increasing stock of human capital, the inducements created by an expanding market, the influence of Enlightenment thinking, or the protections provided by the institutional environment. Most likely, such factors worked together, just as they do in my theoretical framework.

The question of what caused the acceleration in innovation and economic growth that took place during the Industrial Revolution remains debated. However, in order to make progress in understanding the causes of the Industrial Revolution, it is necessary to first establish the nature of the changes that occurred, particularly those that directly affected the rate of technological progress. Documenting, quantitatively, the nature of the changes that took place in the British innovation system during the Industrial Revolution is the primary contribution of this paper.
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A Theory Appendix

This appendix provides details on the theoretical framework discussed in Section 2. Details related to the data and empirical analysis, as well as discussions of additional topics such as the role of government, can be found in the more extensive supplementary appendix, available at http://walkerhanlon.com.

A.1 An endogenous growth model with engineers

This section embeds the emergence of a group of professional inventors into a model of endogenous growth, building on elements from Romer (1990), Unified Growth Theory (Galor & Weil, 2000; Galor, 2011) and using some of the structure of Acemoglu (2002). The model shows how the arrival of a group of professional inventors, engineers, can act as the mechanism that allowed the economy to transition from slow “pre-modern” growth into more rapid “modern” economic growth regime.

A.1.1 Demand

The model is written in continuous-time and, for simplicity, time subscripts are suppressed when possible. The population of the economy is fixed at 1. There is a homogeneous final good with a price normalized to $P=1$. The model admits an infinitely lived representative consumer with CRRA preferences over consumption of the final good:

$$\int_0^\infty \frac{C^{1-\sigma} - 1}{1-\sigma} e^{-\rho t} dt,$$

where $\sigma$ is the coefficient of relative risk aversion and $\rho$ is the time preference parameter. The budget constraint is given by, $C + I + F \leq Y$ where $Y$ is total output of final goods, $I$ is the amount of final goods used in the production of machinery, and $F$ is a fixed cost associated with undertaking research.

A.1.2 Production of final goods

Final goods are produced using skilled labor $H$, unskilled labor $L$, and machines, in a perfectly competitive market with a constant returns to scale technology. The
aggregate production function is,

\[ Y = \frac{1}{1-\beta} \left( \int_0^N x(j)^{1-\beta} dj \right) [(\iota H)^{\alpha} + L^{\alpha}]^{\frac{\beta}{\alpha}} \]  

(2)

where \( N \) is the level of technology (number of machine designs available), \( x(j) \) is the quantity of machine type \( j \) used in production, \( \alpha \in (-\infty, 1) \) and \( \beta \in (0, 1) \) are production function parameters, and \( \iota \in (0, 1) \) is the fraction of high-skilled workers’ time left over for productive activities after they undertake the education necessary to become skilled (so \( 1 - \iota \) reflects the cost, in terms of time, of acquiring skill). Final goods producers solve a standard optimization problem taking as given the wage for low-skilled workers \( (w_L) \), wages for high-skilled workers \( (w_H) \), and a price \( \chi(j) \) for machines of type \( j \). The first order conditions are,

\[ w_L = \beta \frac{1}{1-\beta} \left( \int_0^N x(j)^{1-\beta} dj \right) [(\iota H)^{\alpha} + L^{\alpha}]^{\frac{2-\alpha}{\alpha}} L^{\alpha-1} \]  

(3)

\[ w_H = \beta \frac{1}{1-\beta} \left( \int_0^N x(j)^{1-\beta} dj \right) [(\iota H)^{\alpha} + L^{\alpha}]^{\frac{2-\alpha}{\alpha}} \iota^{\alpha-1} H^{\alpha-1} \]  

(4)

\[ x(j) = \chi(j)^{\frac{2-\alpha}{\alpha}} [(\iota H)^{\alpha} + L^{\alpha}]^{\frac{1}{\alpha}} \]  

(5)

A.1.3 Machine producers

Machine producers hold a perpetual monopoly over their machine design, which they produce using final goods. Machines depreciate fully after use. Setting aside for now the cost of obtaining a machine design, the profits of machine makers are given by \( \pi(j) = (\chi(j) - \phi)x(j) \) where \( \phi \) reflects the cost of producing a new machine in terms of output used. Using the first order conditions from the final goods producers’ problem together with the first order condition for the machine makers’ optimization problem gives \( \chi(j) = \frac{\phi}{1-\beta} \). Thus, the machine price is just a constant mark-up over the marginal cost. Using this, we can rewrite the machine makers’ profits as,

\[ \pi(j) = \beta \left( \frac{1-\beta}{\phi} \right)^{\frac{1-\beta}{\alpha}} [(\iota H)^{\alpha} + L^{\alpha}]^{\frac{1}{\alpha}} \]  

(6)
It is useful to note here that profits are independent of the technology level. However, profit does depend on the number of high and low-skilled workers active in producing final goods.

A.1.4 Occupation choice and technology development

Individuals are endowed with one unit of time and must choose discretely to either become a low-skilled worker or to invest in skills and then become either a high-skilled worker or a professional researcher. Skills depreciate completely each period. Let $E$ denote the quantity of professional researchers (engineers), so $L + H + E = 1$. Low skilled workers earn $w_L$ while high-skilled workers earn $\iota w_H$ (since they have to devote a fraction $1 - \iota$ of their time to becoming skilled). Professional researchers, which also must spend a fraction $1 - \iota$ of their time to become skilled, allocate the remainder of their time to producing new inventions.

New technologies arise from two sources. First, new technologies may be developed by professional researchers (engineers). Since these researchers must have skills, the total time available for research is $\iota E$. In addition, they must pay some fixed cost $f$ to undertake research. Each professional researcher then produces a new machine design with a probability $\eta N$. This productivity scales with $N$, a standard feature of endogenous growth models following Romer (1990). This reflects the idea that professional researchers are more likely to generate a new technology if they have more existing ideas and tools to work with. As (Romer, 1990) explains, “The engineer working today is more productive because he or she can take advantage of all the additional knowledge accumulated as design problems were solved...” The overall number of new technologies generated by the professional research sector within a period is then $\eta N \iota E$.

In addition, new technologies may be developed by high-skilled workers as a serendipitous byproduct of production.\(^{46}\) This occurs for each high-skilled worker with probability $\gamma N$. It is useful to note that making the probability of a serendipitous discovery increasing in $N$ is not a vital assumption for the model, but it is

\(^{46}\)The assumption that only high-skilled workers and not low-skilled workers generate new inventions as a byproduct of production is not critical for the main results of the theory, but it seems more reasonable to confine the development of new technologies to only those with skills.
useful for helping the model match the patterns observed in the data.\footnote{Specifically, if instead the rate of serendipitous discoveries occurred at rate $\gamma$ rather than $\gamma N$, then the growth rate of technologies generated through this channel is declining over time. That does not match the patterns in the patent data, which show that innovations by non-engineers grew at a constant (but low) rate during my study period.} Given this formulation, the number of new technologies generated through this channel is $\gamma N t H$.

Motivated by the results presented in my empirical analysis, I make the following key assumption:

**Assumption:** $\eta > \gamma$, so professional researchers are more productive at generating new technologies than high-skilled workers engaged mainly in goods production.

Technological change in the economy is $\dot{N} = \gamma N t H + \eta N t E$ and the rate of change is,

$$\frac{\dot{N}}{N} = \gamma t H + \eta t E \quad (7)$$

The discounted present value of a new machine design depends on the profits of machine makers according to $V = (\pi + \dot{V})/r$, where $r$ is the interest rate and $\dot{V}$ accounts for changes in future profits.\footnote{It is worth noting that $\dot{V} \leq 0$ in this model. To see this, note that profits depend only on the amount of skilled and unskilled workers employed in final goods production. As shown below, for low levels of $N$ all workers will be used in final goods production, and this amount will fall if at some point some workers begin choosing to become researchers. Thus, profits can only fall over time in the model.}

When a professional researcher develops a new technology, their ability to capture the rents from their design depends on the strength of intellectual property protection. The strength of IP protection is represented by the parameter $\lambda \in (0, 1)$ which reflects the probability that an inventor retains ownership over a design. If they retain ownership, then they sell of the design to one out of a large group of potential machine making firms, thus capturing the full discounted present value of the invention. If they do not, I assume that the design is appropriated by the government which sells the design for the full value and then distributes the proceeds to all individuals in the economy through equal lump-sum payments. For simplicity, I assume that when high-skilled workers generate serendipitous inventions they are not able to monetize
the value. Instead, the invention is appropriated by the government, auctioned off to a machine firm, and the value is returned to individuals through lump-sum transfers. This is not a critical assumption. It is made only because it simplifies the exposition of the model and helps emphasize the fact that growth during the pre-modern period is not dependent on the availability of intellectual property protection.

The expected return to low-skilled workers, high-skilled workers, and researchers, respectively, is,

\[ ER_L = w_L = \beta(1 - \beta)^{1-2\beta} \phi^{\frac{\beta-1}{\beta}} [(\lambda H)^\alpha + L^{\alpha}]^{\frac{1-\alpha}{\alpha}} L^{\alpha-1} N \]  
\[ \text{(8)} \]

\[ ER_H = w_H = \beta(1 - \beta)^{1-2\beta} \phi^{\frac{\beta-1}{\beta}} [(\lambda H)^\alpha + L^{\alpha}]^{\frac{1-\alpha}{\alpha}} \lambda^{\alpha} H^{\alpha-1} N \]  
\[ \text{(9)} \]

\[ ER_E = \lambda\eta V N - f = \frac{\lambda\eta\beta}{r} \left( \frac{1 - \beta}{\phi} \right)^{\frac{1-\beta}{\phi}} [(\lambda H)^\alpha + L^{\alpha}]^{\frac{1}{\alpha}} N + \frac{\lambda\eta\dot{V}}{r} N - f \]  
\[ \text{(10)} \]

I assume that professional researchers are able to insure each other against the risk of not producing an invention in any particular period, so that in choosing an occupation they care only about the expected returns.

In equilibrium, individuals will choose between being a low-skilled worker, a high-skilled worker, or a researcher, to maximize their expected return. Since both high and low-skilled workers are vital to the production of final goods (since \( \alpha < 1 \)), we know that there will be positive quantities of both of these types of workers. This implies that in equilibrium \( ER_H = ER_L \). Using this and Eqs. 8 and 9 we can solve for the equilibrium relationship between \( L \) and \( H \). This is \( H/L = \lambda^{\frac{\alpha}{1+\alpha}} \). This equation tells us that when high and low-skilled workers are substitutes (\( \alpha > 0 \)) the share of high-skilled workers in the economy will increase when the costs of becoming skilled falls (higher \( \lambda \)). Otherwise, if \( \alpha < 0 \), the share of high-skilled workers will fall as the cost of obtaining skill falls. The relevant case for our setting is likely to be \( \alpha > 0 \), so that locations where it is easier to acquire skills also have more skilled workers.

One feature in Eq. 10 that is worth noting is that the \( \lambda \) parameter increases the returns to being a professional researcher in two ways. First, there is a direct effect on
engineers through easier access to skills. Second, easier access to skills raises the return to being a researcher by increasing the number of skilled workers in the economy able to work with the new technologies that professional researchers discover. This channel, represented by the $\iota H$ term, reflects another connection between the theory and the empirical setting, where historical evidence suggests that the availability of skilled craftsmen in England who could construct new machines played an important role in incentivizing the development of those technologies.\footnote{See Mokyr (2009), Chapter 6.}

**A.1.5 Development path and key results**

Consider the development path of the economy starting from a very low initial technology level. The first useful prediction of the theory is that the professional research sector will be inoperative when the technology level is sufficiently low.

**Prop. 1:** There exists some $N$ such that for all $N < N$, $ER_E < ER_H = ER_L$ when $E = 0$ and therefore no individuals choose to become professional researchers.

**Proof of Prop. 1:** This follows directly from the fact that $ER_E$, $ER_H$ and $ER_L$ are continuous functions of $N$ and that $\lim_{N \to 0} ER_E < 0$ while $\lim_{N \to 0} ER_H = 0$.

The intuition here is simple. Since the productivity of researchers scales with $N$, at low levels of $N$ they are unproductive, and so it does not pay to become a professional researcher given the fixed costs involved.

Starting from an initially low level of $N$, Proposition 1 tells us that the economy will initially be one in which there are no professional researchers. This initial “pre-modern” period is characterized by relatively slow growth, which may be very slow if $\gamma$ is low, and no professional research sector. This pre-modern period may potentially last for a very long time; under certain conditions the economy may be stuck in pre-modern growth forever, as explained shortly. In periods characterized by pre-modern growth (where $E = 0$) we have the following equilibrium allocations of high and low skilled workers,

$$\tilde{H} = \frac{1}{1 + \frac{\gamma}{1-\alpha}} \quad \tilde{L} = \frac{\frac{\gamma}{1-\alpha}}{1 + \frac{\gamma}{1-\alpha}}$$
derived by using the conditions $ER_L = ER_H$ and $H + L = 1$.

It is important to note during pre-modern growth, technological progress is not dependent on the availability of intellectual property protection, so the model can capture historical periods in which new technologies were developed even though inventors received little or no monetary reward from their discoveries.

Next, I show that when the professional research sector is operating, the growth rate increases.

**Prop. 2:** When $\eta > \gamma$, the growth rate is increasing in $E$.

**Proof of Prop. 2:** The growth rate $g = \dot{N}/N = (\gamma_1 H + \eta_1 E)$. Using $H + L + E = 1$ and substituting in $L = H_1 \frac{\mu}{1 - \mu}$, we have $H = (1 - E)/(1 + \mu_1 \frac{\alpha}{1 - \mu})$. Thus,

$$\frac{\dot{N}}{N} = \frac{\gamma_1}{1 + \mu_1 \frac{\alpha}{1 - \mu}} + E \left( \eta_1 - \frac{\gamma_1}{1 + \mu_1 \frac{\alpha}{1 - \mu}} \right)$$

which is increasing in $E$ when $\eta > \gamma$.

The growth rate in the proof above has an intuitive structure. The first term is the rate of growth in the pre-modern period while the second term is the product of the share of researchers in the economy and the difference between the rate that they produce inventions ($\eta_1$) and the rate of serendipitous discovery by high-skilled workers ($\gamma_1$) and accounting for the fact that only a fraction of non-researchers end up becoming skilled (reflected in the $1 + \mu_1 \frac{\alpha}{1 - \mu}$ term).

The next proposition describes the conditions under which the economy will eventually transition into modern growth. It is useful to begin by defining the following key condition:

**Condition 1:** $(1 - \beta) \lambda \eta_1 - (\gamma_1 \sigma)/(1 + \mu_1 \frac{\alpha}{1 - \mu}) > \rho$

**Prop. 3:** If Condition 1 holds, there exists some $\bar{N}$ such that for any $N > \bar{N}$, $ER_E > ER_H = ER_L$ when $E = 0$ and therefore at least some individuals choose to become researchers. If Condition 1 fails, then there is no $N$ such that $ER_E > ER_H = ER_L$ when $E = 0$ and the professional research sector never emerges.
Proof of Proposition 3: To prove the first statement, by contradiction, suppose that \((1 - \beta)\lambda_\eta - (\gamma_\ell\sigma)/(1 + \nu^{-\alpha}) > \rho\) but that \(ER_L > ER_E\) for all \(N\). This implies that \(\lim_{N \to +\infty} ER_L - ER_E \geq 0\).

Since there is no professional research sector, the economy will be in a balanced growth path characterized by \(E = 0\), \(H = \frac{1}{1 + \nu^{-\alpha}}\), \(L = \frac{\nu^{-\alpha}}{1 + \nu^{-\alpha}}\), and \(\dot{V} = 0\).

Thus,

\[
\lim_{N \to +\infty} N \left[ \beta(1 - \beta) \frac{1 - 2\beta}{\phi} \frac{\beta - 1}{\phi} [(\nu H)^\alpha + L^\alpha] \frac{1 - \alpha}{\alpha} L^{\alpha - 1} - \frac{\lambda \eta \beta}{\varphi} \left( \frac{1 - \beta}{\varphi} \right) \frac{1 - \beta}{\phi} [(\nu H)^\alpha + L^\alpha] \frac{1 - \alpha}{\alpha} \right] \geq 0
\]

This is true only if,

\[
\beta(1 - \beta) \frac{1 - 2\beta}{\phi} \frac{\beta - 1}{\phi} [(\nu H)^\alpha + L^\alpha] \frac{1 - \alpha}{\alpha} L^{\alpha - 1} \geq \frac{\lambda \eta \beta}{\varphi} \left( \frac{1 - \beta}{\varphi} \right) \frac{1 - \beta}{\phi} [(\nu H)^\alpha + L^\alpha] \frac{1 - \alpha}{\alpha}
\]

Substituting in for \(L\) and \(H\) and solving gives, \(r \geq (1 - \beta)\lambda_\eta\).

We now need to substitute in for \(r\) using the intertemporal optimization condition. Since the professional research sector does not operate in this scenario, the steady state growth rate is is \(\dot{N}/N = \gamma_\ell H = \gamma_\ell/(1 + \nu^{-\alpha})\). The intertemporal optimization condition implies that \((r - \rho)/\sigma = \gamma_\ell/(1 + \nu^{-\alpha})\). Solving for \(r\) and substituting in we have,

\[
\rho \geq (1 - \beta)\lambda_\eta - \frac{\gamma_\ell \sigma}{(1 + \nu^{-\alpha})}
\]

But this contradicts the initial assumption.

To prove the second statement, given Proposition 1, it is sufficient to show that \((1 - \beta)\lambda_\eta - (\gamma_\ell\sigma)/(1 + \nu^{-\alpha}) < \rho\) implies \(d(ER_E - ER_L)/dN < 0\) for any \(N\).

\[
\frac{d(ER_E - ER_L)}{dN} = \frac{\lambda \eta \beta}{\varphi} \left( \frac{1 - \beta}{\varphi} \right) \frac{1 - \beta}{\phi} [(\nu H)^\alpha + L^\alpha] \frac{1 - \alpha}{\alpha} L^{\alpha - 1} - \beta(1 - \beta) \frac{1 - 2\beta}{\phi} \frac{\beta - 1}{\phi} [(\nu H)^\alpha + L^\alpha] \frac{1 - \alpha}{\alpha} L^{\alpha - 1}
\]

Since \(\dot{V} \leq 0\), for \(d(ER_E - ER_L)/dN < 0\) it is sufficient that,

\[
\frac{\lambda \eta \beta}{\varphi} \left( \frac{1 - \beta}{\varphi} \right) \frac{1 - \beta}{\phi} [(\nu H)^\alpha + L^\alpha] \frac{1 - \alpha}{\alpha} L^{\alpha - 1} < 0
\]
Reorganizing and substituting in for L and H, we have,

\[(1 - \beta)\lambda \eta < r\]

Thus, whenever this condition holds, \(d(ER_E - ER_L)/dN < 0\). It remains to show that this must hold under the initial assumption of \((1 - \beta)\lambda \eta - (\gamma \mu \sigma)/(1 + \tau) < \rho\). This can be reorganized to obtain \((1 - \beta)\lambda \eta < \rho + (\gamma \mu \sigma)/(1 + \tau)\). Thus, a sufficient condition for \((1 - \beta)\lambda \eta < r\) is \(\rho + (\gamma \mu \sigma)/(1 + \tau) \leq r\). This can be reorganized to,

\[\gamma \mu \sigma \leq (1 - \beta)\lambda \eta \leq (1 - \beta)\lambda \eta + (\gamma \mu \sigma)/(1 + \tau) \leq r\]

To see that this must be true note that the intertemporal optimization condition requires that \((r - \rho)/\sigma = g\) where \(g\) is the growth rate of the economy, and that \(g \geq \gamma \mu /(1 + \tau)\) (see Proposition 3). Thus, if \((1 - \beta)\lambda \eta - (\gamma \mu \sigma)/(1 + \tau) < \rho\) it can never be the case that \(ER_E > ER_L\) with \(E = 0\) and so the professional research sector can never begin operating.

The intuition here is that, under Condition 1, the return to professional researchers increases more rapidly with \(N\) than returns in the production sector (when \(E = 0\)). As a result, eventually the return to becoming a researcher exceeds the wage of production workers and some individuals have an incentive to become professional researchers.\(^{50}\)

Proposition 2 is a central result of the theory. It tells us that the professional research sector emerges only under certain conditions. In particular, the emergence of the professional research sector depends crucially on the availability of institutions that allow inventors to monetize their inventions, reflected in the \(\lambda\) parameter.\(^{50}\)

\(^{50}\)This begs the question of why the return to the research sector does not continue to rise faster than wages in the production sector after the research sector begins to operate. The reason that this does not happen is that as fewer individuals choose to become workers, the profits of the machine making firms fall (see Eq. 6) pulling down the value of new inventions and thus the returns to becoming a professional researcher.
Whether a professional research sector emerges also depends on the ease with individuals can acquire skills, reflected in the $\iota$ parameter (note that the left-hand side of Condition 1 is increasing in $\iota$). Only when these conditions are satisfied will a professional research sector eventually emerge, allowing growth to accelerate. Thus, Proposition 2 connects the model to the features of the historical setting, specifically the availability of useful knowledge, a culture of learning, access to training in craft skills (such as through apprenticeships), and institutions that allowed inventors to monetize inventions.

Once modern economic growth begins, the economy approaches a new long-run balanced growth path. On the equilibrium balanced growth path, $ER_L = ER_H = ER_E$, $\dot{V} = 0$, and as $N \to +\infty$ the economy approaches fixed shares of researchers, skilled, and unskilled workers (described in Appendix A.1.6).\footnote{Note that the no-Ponzi game condition requires that $(1 - \sigma) g < \rho$, which restricts the admissible set of parameter values.} The long-run ratio of researchers to production workers in the economy is,

$$\theta = \frac{E}{H + L} = (1 - \beta) \lambda \eta \iota - \frac{\gamma \sigma \iota^{1-\alpha}}{1 + \iota^{1-\alpha}} - \rho$$  \hspace{1cm} (11)

This share is increasing in the productivity of researchers $\eta$, as we would expect, as well as the importance of machines in the production function $(1 - \beta)$ and the strength of IP protection represented by $\lambda$. The share is decreasing in the rate at which high-skilled manufacturing workers generate new technologies ($\gamma$), decreasing in the time discount factor $\rho$, and decreasing in the coefficient of relative risk aversion $\sigma$. This is intuitive given that the value of research is mainly realized in the future.

As indicated by Prop. 2, the long-run growth rate in the modern economy with an active professional research sector is faster than the rate experienced in the pre-modern period. Thus, the emergence of professional researchers has pushed the economy onto a more rapid growth path. How much growth increases depends on the difference between $\eta$ and $\gamma$.

Finally, it is useful to show that the model provides additional predictions that are consistent with the historical record:

**Prop. 4:** When Condition 1 holds, the economy converges to a long-run balanced
growth path in which the share of skilled workers in the economy is higher than the share during the pre-modern growth period.

**Proof of Proposition 4:** To prove this proposition it is sufficient to show that, under Condition 1, \( \tilde{L} > L^* \), where \( \tilde{L} = 1/(1 + \nu^{\alpha}) \) is the amount of low-skilled workers in the pre-modern period and \( L^* \) is given by Eq. 12. It will be the case that \( \tilde{L} > L^* \) when,

\[
\frac{1}{1 + \nu^{\alpha}} > \frac{\eta \sigma \iota + \rho}{(1 - \beta) \lambda \eta (1 + \nu^{\alpha}) - \gamma \sigma \iota (1 + \nu^{\alpha}) + \eta \sigma \iota (1 + \nu^{\alpha})}
\]

\[
(1 - \beta) \lambda \eta (1 + \nu^{\alpha}) - \gamma \sigma \iota (1 + \nu^{\alpha}) + \eta \sigma \iota (1 + \nu^{\alpha}) > \eta \sigma \iota (1 + \nu^{\alpha}) + \rho (1 + \nu^{\alpha})
\]

\[
(1 - \beta) \lambda \eta (1 + \nu^{\alpha}) - \gamma \sigma \iota \nu^{\alpha} > \rho (1 + \nu^{\alpha})
\]

\[
(1 - \beta) \lambda \eta = \frac{\gamma \sigma \iota \nu^{\alpha}}{(1 + \nu^{\alpha})} > \rho
\]

This is exactly Condition 1.

Thus, the onset of modern economic growth is characterized not just by an accelerated rate of technological progress but also by an increase in the share of skilled individuals in the economy.\textsuperscript{52}

**A.1.6 Long-run balanced growth path**

Once modern economic growth begins (if it does), the economy begins to approach a new long-run stead state characterized a fixed proportion of high-skilled workers,\textsuperscript{52}

\textsuperscript{52}It is worth noting that this increase is driven by the demand for skilled workers in the professional research sector. The ratio of skilled to unskilled production workers is unchanged.

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low-skilled workers, and professional researchers. In equilibrium, \(ER_L = ER_E\), so,

\[
\beta(1 - \beta) \frac{1 - \beta}{\beta} \phi^{\frac{\alpha - 1}{\alpha}} [(iH)^{\alpha} + L^{\alpha}]^{\frac{1 - \alpha}{\alpha}} L^{\alpha - 1} N = \frac{\nu \lambda \eta \beta}{\rho} \left(1 - \beta\right) \frac{1 - \beta}{\phi} [(iH)^{\alpha} + L^{\alpha}]^{\frac{1}{\alpha}} N + \frac{\nu \lambda \eta \dot{V}}{\rho} N - f
\]

On the balanced growth path, \(\dot{V} = 0\) and so as \(N \to +\infty\) the economy approaches,

\[
\beta(1 - \beta) \frac{1 - \beta}{\beta} \phi^{\frac{\alpha - 1}{\alpha}} [(iH)^{\alpha} + L^{\alpha}]^{\frac{1 - \alpha}{\alpha}} L^{\alpha - 1} = \frac{\nu \lambda \eta \beta}{\rho} \left(1 - \beta\right) \frac{1 - \beta}{\phi} [(iH)^{\alpha} + L^{\alpha}]^{\frac{1}{\alpha}}
\]

This together with \(H = \nu \frac{\alpha}{\alpha} L\) can be used to show,

\[
L = \frac{r^{\alpha - 1}}{(1 - \beta) \lambda \eta(1 + \nu \frac{\alpha}{\alpha})}
\]

\[
H = \frac{r^{\alpha - 1}}{(1 - \beta) \lambda \eta(1 + \nu \frac{\alpha}{\alpha})}
\]

\[
E = 1 - \frac{r^{\alpha - 1}}{(1 - \beta) \lambda \eta}
\]

The standard intertemporal optimization condition implies that \((r - \rho)/\sigma = g = \gamma iH + \eta iE\). Substituting for \(H\) and \(E\) and solving for \(r\), we have,

\[
r = \frac{(1 - \beta) \lambda \eta(1 + \nu \frac{\alpha}{\alpha})(\eta i \sigma + \rho)}{(1 - \beta) \lambda \eta(1 + \nu \frac{\alpha}{\alpha}) - \gamma i \frac{\alpha}{\alpha} \sigma + \eta \sigma(1 + \nu \frac{\alpha}{\alpha})}
\]

Substituting this back in, we have,

\[
L^* = \frac{\eta i \sigma + \rho}{(1 - \beta) \lambda \eta(1 - \nu \frac{\alpha}{\alpha}) - \gamma i \frac{\alpha}{\alpha} \sigma + \eta \sigma(1 + \nu \frac{\alpha}{\alpha})}
\]

\[
H^* = \frac{\nu \frac{\alpha}{\alpha}(\eta i \sigma + \rho)}{(1 - \beta) \lambda \eta(1 - \nu \frac{\alpha}{\alpha}) - \gamma i \frac{\alpha}{\alpha} \sigma + \eta \sigma(1 + \nu \frac{\alpha}{\alpha})}
\]
The growth rate is,

\[ g = \frac{\gamma \iota}{1 + \iota^{\frac{\alpha}{1 - \alpha}}} + E \left( \eta - \frac{\gamma \iota}{1 + \iota^{\frac{\alpha}{1 - \alpha}}} \right) \]

Here, the first term is the growth rate of the economy when there are no professional researchers, and the second term is the share of professional researchers in the economy multiplied by the difference between the rate at which professional researchers produce innovations and the rate at which high-skilled workers produce innovations, scaled by \( 1 + \iota^{\frac{\alpha}{1 - \alpha}} \) to reflect the fact that if the share of professional researchers falls there is a less-than-proportional increase in the share of high-skilled workers in the economy.